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Packaging and Mounting of In-Fibre Bragg Grating Arrays for Structural Health Monitoring of Large Structures

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ABSTRACT

A simple and inexpensive method has been developed for the application and bonding of optical fibre sensor networks to large structures for Structural Health Monitoring applications. The method makes use of a vacuum-assisted infusion technique using a low-cost epoxy resin which was found suitable for surface attachment. Mechanical tests showed no creep of the cured resin, and the response of Bragg grating based sensors was linear up to 5500 με. There was no hysteresis in the response and the sensitivity displayed at least equals that of a standard electrical resistance gauge.

A system for the management and transport of long optical fibres with arrays of sensors was proposed which facilitates safe and easy movement of all sensors from production to application. During application, the same resin infusion technique can be adapted to account for parameters in the size and shape of the structure and the operating environment. A laboratory simulation showed that sensors can be bonded over large distances (>10 m) thus making a large-scale, optical fibre sensor network feasible. This work has also revealed a tendency of the fibre to break under load in the splice region where it is connected to the cabled fibre. This is expected as it is the weakest region of the fibre and future work will focus on isolating this region of the packaging from the strain experienced by the structure to which it is bonded.

Finally, the report lists other recommendations for further work which includes an evaluation of the long-term performance of this technique.

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Executive Summary

The work described in this report was carried out by the Australian Defence Science and Technology Organisation (DSTO) contributing in part to the wider research program sponsored by the US Office of Naval Research (ONR) under Grant No. N00014-09-1-0364. This is a collaborative, three-year research program entitled 'Structural Health Monitoring Through Environmental Excitation and Optical Fibre Sensors'. It involves participants from the Naval Surface Warfare Centre (NSWC) - Carderock Division, US Naval Academy, Co-operative Research Centre for Advanced Composite Structures (CRCACS) and DSTO.

Under Milestone 4 of this program, the research activity focuses on the development and validation of packaging and bonding techniques for reliable, robust and repeatable strain measurement in structures using in-fibre Bragg gratings. The report gives a detailed account of that work which includes; (i) selection of materials, (ii) development of the technique, (iii) mechanical evaluation of surface bonded sensors, (iv) management of fibre sensor arrays and (v) adaptation of the technique for in-situ applications.

The results from the small-scale laboratory experiments identified a suitable epoxy resin system for bonding the fibre sensors to composite test samples. Mechanical tests showed that the resin does not show creep, the sensor behaves linearly up to 5500 $\mu\varepsilon$, there is no hysteresis in the response and the sensitivity displayed is at least equal to that of a standard electrical resistance gauge. A technique for the management of long optical fibres with arrays of in-fibre Bragg sensors was proposed which facilitates safe and easy transport of such fibre sensors from the production facility to the application site. During application of the fibre array, the resin infusion technique can be adjusted to account for the particular circumstances of the application. A laboratory simulation showed that sensors can be bonded over large distances (>10 m) thus making this technique feasible.

This work has also revealed a tendency for the fibre to break under load in the splice region where it connects to the cabled fibre. This is expected as it is the weakest region of the fibre and future work will focus on isolating this region of the packaging from the strain experienced by the structure to which it is bonded.

Finally, the report lists other recommendations for further work which aims to extend knowledge in this technique, including its long-term performance. Overall, the outcome of this work is promising, offering a simple, inexpensive and easy-to-apply method for the application of in-fibre grating arrays to large structures.

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Dr Ivan Grabovac is a senior research scientist in the Maritime Platforms Division. Since joining DSTO in 1973 he gained a broad range of experience in the field of engineering polymers used for aerospace and naval applications. Among other, current interest includes the use of fibre optic sensors for structural health monitoring.

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Contents

Abbreviations

CFRP	Carbon Fibre Reinforced Polymer
FBG	Fibre Bragg Grating
FGI	Fiberglass International
FO	Fibre Optic
FOS	Fibre Optic Sensor
GFRP	Glass Fibre Reinforced Polymer
HDPE	High Density Polyethylene
LED	Light Emitting Diode
MHC	Mine Hunter Coastal
MTS	Materials Testing Services
OF	Optical Fibre
OSA	Optical Spectral Analyser
PSA	Pressure Sensitive Adhesive
R&D	Research and Development
RAN	Royal Australian Navy
RIP	Resin Injection Point
RTM	Resin Transfer Moulding
SEM	Scanning Electron Microscope
SG	Strain Gauge
SHM	Structural Health Monitoring
SMF	Single Mode Fibre
VARTM	Vacuum Assisted Resin Transfer Moulding

1. Introduction

The use of Bragg gratings in optical fibres to measure strain was first reported in the literature in the mid 1980's [1]. Fibre Bragg gratings (FBG's) offer a number of key advantages over existing strain sensing technology. They are immune to electromagnetic interference, tolerant of high temperatures, self referencing and can support many spatially separated sensors along a single optical fibre. Despite these advantages there has been a relatively slow transition of the technology to the marketplace. There are a number of reasons for this; the equipment required to interrogate the sensors is costly and often sensitive to harsh environments, there is a lack of conclusive information about sensor reliability/durability and the fibres are fragile. In contrast, the existing electrical foil strain gauge technology is well-understood and suitable for most discrete sensing applications. Furthermore, there has been limited experience in the field with packaging, bonding and networking techniques for optical fibres particularly on large and/or complex structures.

The work described in this report is motivated by a larger collaborative research program sponsored by the US Office of Naval Research entitled '*Structural Health Monitoring (SHM) Through Environmental Excitation and Optical Fibre Sensors*'. The ultimate goal of the larger program is the demonstration and validation of a large area, vibration-based structural health monitoring system on a composite structure using simulated environmental excitation and a network of surface-mounted fibre Bragg gratings for response measurement. This report describes one stage of the progress towards this goal with the development of a customised packaging, handling and bonding technique for application of FBG arrays to large composite structures.

The report begins by providing some background material on the current status of packaging techniques for FBG sensors and recently reported SHM applications on large structures using FBGs. A detailed account then follows of the experimental work leading to the development of a customised solution for packaging and application of FBG arrays, looking in particular at the following areas; (i) selection of materials, (ii) development of technique, (iii) mechanical evaluation of surface bonded sensors, and for the large-scale structural application it includes (iv) the development of handling processes for fibre sensor arrays and (v) on-site application.

2. Background

The precise methodology for packaging FBGs is very much dependent on the intended application. For example, whether the FBG's are retrofitted to an existing structure [2] or embedded into the structure at the time of construction [3]. The materials used in the structure and the environmental operating conditions must also be considered. Regardless of the application, issues such as *birefringence*, *temperature* and the *strain transfer mechanism* are all reported [2-6] to have an effect on the measurement precision and therefore should be taken into account when considering an appropriate packaging and application technique.

2.1 Commercially Available FBG Packaging

Commercially available sensor packages for FBGs have appeared in the marketplace over the past decade. These sensors are available pre-packaged for a variety of applications and structures. By choosing these sensors the user involvement regarding the packaging is minimal as all the necessary instructions and materials are usually provided by the manufacturer. Examples of companies providing these products are Micron Optics, Fibre Optic Sensing Solutions and Systems, Smartec (recently acquired by Roctest), Insensys, HBM, Oz Optics, Luna Technologies and Fibersensing. Generally, these sensor packages are supplied for single point measurements of strain and are often supplied with temperature compensation if required. Packaged sensors may be daisy-chained together to provide distributed sensing. Some examples of these packages are shown in Figure 1.

(a)

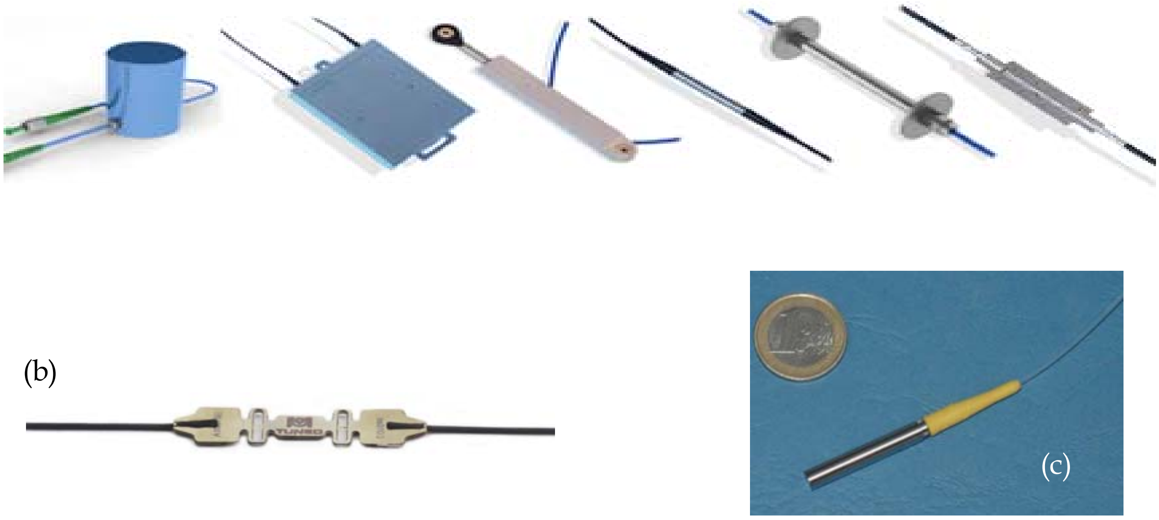

Figure 1: Examples of packaged FBG sensors for strain sensing. (a) Product range from Fibersensing[1], (b)Epoxy mounted standard strain gauge from Micron Optics[2] (c) Temperature compensated strain gauge from 'Fibre Optic Sensing Solutions and Systems'[3].

Some companies also provide FBG arrays directly packaged in tape for secondary bonding to the structure, which avoids the need for daisy-chaining individual packaged FBGs to provide distributed sensing. Generally, these arrays are fabricated to the customers' requirements. Some examples are shown in Figure 2.

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1 http://www.fibersensing.com
2 http://www.micronoptics.com/sensors_products.php
3 http://www.fos-s.be/

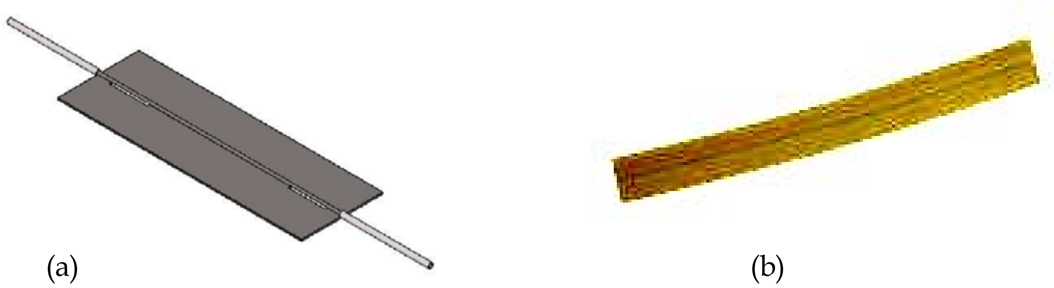

Figure 2: Examples of Smartec packages for distributed sensing including (a) weldable tape with embedded FBG and (b) thermoplastic composite tape with embedded FBG array for distributed sensing[4].

2.2 Structural Health Monitoring of Large Structures using FBG's

Concurrently, with the development of new packaging techniques, research is also being conducted into new applications for distributed fibre optic sensing (FOS) systems. This research is focussed on large structures where the application of distributed, non-intrusive sensing systems is most advantageous. Most of the documented research in these areas has focussed on the interrogation and analysis methodology for the FBG's rather than the processes for actually applying these sensor arrays. In fact, there is very little research in the published literature relating to practical techniques for incorporating distributed FBG arrays into or onto structures. A few of the reported schemes are outlined in the subsequent paragraphs.

An operational loads monitoring system for wind turbine blades was demonstrated [7] using FBGs surface-mounted onto glass fibre composite sensor pads which were then retrofitted to the rotor blades of the wind turbine. In this case a series of daisy-chained sensor pads each of 400 mm length was used to provide a series of average strain measurements along the blades. The entire FBG sensor pad length was adhered to the blades and then the whole pad area on the blade was also coated in adhesive for protection [7].

Researchers at BAE Systems have demonstrated a distributed FBG system which was incorporated into the composite mast of a luxury cruising yacht during construction. Eight sensor-bearing fibres each containing up to 5 gratings on the array were placed manually in the 35 m carbon fibre mast during the wet lay-up manufacturing process. The embedded sections of the fibre were clad only in an acrylate primary buffer and the egress points were protected by a series of protective polymer jackets [8]. The same research team also retrofitted an optical strain gauge rosette to the wing of a test aircraft (Jetstream 31). The optical strain gauges were embedded in polyimide film which was then hot-bonded to the external lower surface of the wing using a standard hot bonding process developed for electrical foil strain gauges. Once bonded the sensors were covered with a protective layer of aerospace sealant and the whole area was painted [8].

[4] http://www.smartec.ch/products.htm

More recently, there has been significant building activity in certain parts of Asia with the construction of new civilian infrastructure such as bridges, highways and buildings. With this increased activity there has been the opportunity to incorporate new FBG sensing technologies for SHM of this infrastructure.

Li *et al.* reported on the integration of FBG sensors into smart stay cables. The FBG sensors were first embedded into a glass fibre reinforced polymer (GFRP) bar. These bars were then incorporated into the twisted steel assembly of the cable. The egress point of the bare fibre was protected with a pyro-condensation tube and further shielded with a copper sheath [9].

Chan *et al.* permanently installed a network of 40 multiplexed FBGs onto the Tsing Ma suspension bridge deck in Hong Kong [10]. This bridge is the sixth largest span suspension bridge in the world [11]. The FBGs were packaged by mounting them on nitinol strips (thickness of 7.5 μm), which were then sandwiched between two Teflon[5] sheets to minimise the thickness and achieve evenness of epoxy between the FBG and the nitinol sheets. The packaged FBG sensors were bonded to the nitinol sheets using epoxy resin and the assembly cured in an oven at 80°C for 5 h. Nitinol is a room temperature super-elastic metal which is corrosion-resistant and can withstand 8% elongation without plastic deformation. This package is then bonded directly to the structure using two-part epoxy. The fusion splice connecting the acrylate-coated fibre to the cabled fibre is then protected from the elements by a weather-proof enclosure.

2.3 FBG Sensor Packaging and Mounting for Large Scale Applications – Perceived Challenges

The process of developing a sensor packaging and mounting solution for a particular application should address all (or most) problems at the laboratory development and evaluation stage. For SHM of a composite structure with a large surface area (>10 m^2), multiple FBG arrays running parallel to one another, Figure 3, is being considered for *in-situ* sensing applications. The literature does not appear to cover such applications. The approach taken in this project involved a two-step development process; (i) the laboratory-based research and development and (ii) an on-site application. Ideally, these steps should not be developed in isolation since, for example, it may turn out that the materials, techniques and experience used in the laboratory cannot be transferred simply into practice.

Some of the important issues for large-scale field applications are:

- **Pre-packaging** of a small number of fibre optic (FO) sensors is normally carried out for commercial products as outlined in the previous section. For large-scale sensor applications where hundreds of sensors can be used, an alternative method of handling such sensor system needs to be developed. A single fibre up to 5 or 10 m in length may contain 10 or 20 sensors in the array therefore, from a practical viewpoint these should not be resin encapsulated prior to service application due to the likelihood of handling difficulties. In such cases, the packaging and bonding should be done *in-situ* and, if possible, in one step. The pre-packaging should also involve some form of fibre shielding to protect fibres during handling and transportation.

[5] Teflon® is a registered trademark of E. I. du Pont de Nemours and Company or its affiliates, http://www2.dupont.com/Teflon/en_US/index.html

- **Transportation** of a large number of FO sensors to the site of application should be planned to avoid any mechanical damage to the fibres during transit including the ease of onsite application.
- **Alignment** of the multi-strand fibre arrays of sensors for the representative *in-situ* application considered shows, as an example, a typical fibre and sensor separation at approx. 0.5 m, Figure 3. Additionally, such alignment could in principle form a pattern of coordinates consistent with those of a structure for easier damage location and identification.

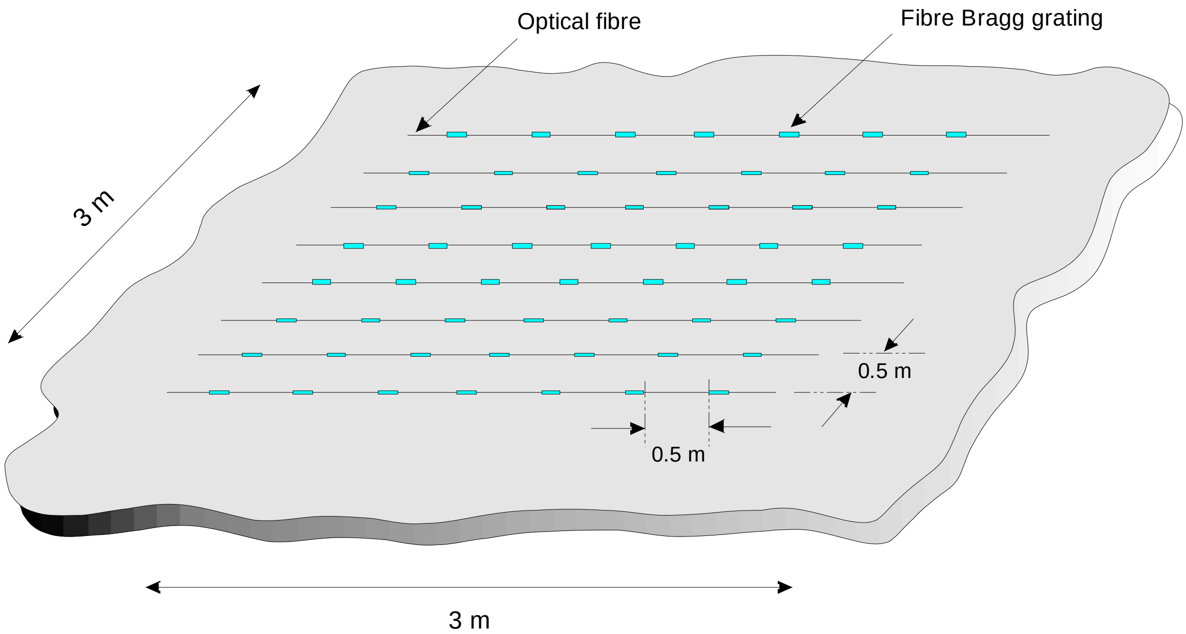

Figure 3: Authors' impression of a typical sensor distribution over a representative large structure.

- **Packaging and mounting** on, e.g. composite structure, must not compromise strain transfer to the sensor(s), i.e. the use of the bonding medium must not contribute to relaxation or creep under load. Generally, thermo-set resin systems are considered suitable for this application as they exhibit no measurable material distortion after full cure.
- **Protection** of the sensor system installed on a structure must be provided against damage due to abrasion, mechanical interference, environmental effects or any combination thereof. Unless temperature measurements are required, protection against heating/cooling to minimise thermal strains or some means of temperature compensation should be considered. Protection of the sensor system from the environment, and in particular moisture, is very important especially if system is to be used over an extended period (years) on a composite structure.

3. Experimental Methodology

3.1 Small-Scale Laboratory Work

In this section the evolutionary development leading to an *in-situ* packaging and mounting system for a network of surface-mounted FBG sensors is described. The main aim was to develop a simple, easy-to-apply and cost effective method for packaging/mounting by using commercially available materials off-the-shelf. Furthermore, it was considered advantageous if the developed technique can be easily adapted for wide variety of on-site applications where the scale of the structure and environmental conditions may vary.

For all of the laboratory testing described in this report, a standard communications-grade, single-mode optical fibre supplied by Fiber Logix[6] was used. A schematic diagram of the composition of the optical fibre and the size relationship between different layers is shown in Figure 4 [12]. These dimensions highlight the fragility of the fibre and the need for care when handling and working with them. The coating was removed from the fibre prior to inscription of the FBG and the fibres were stored in a desiccant container after inscription, prior to mounting on the test specimens. The FBGs were 3 mm long apodised gratings fabricated using a standard phasemask exposure technique.

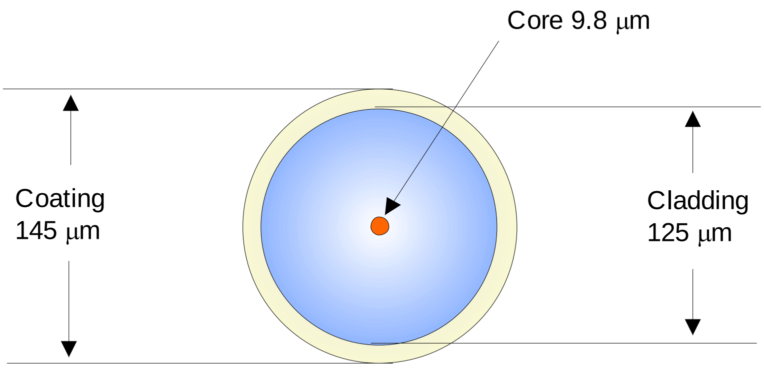

Figure 4: Cross-section and composition of optical fibre [12].

The aim of the small-scale laboratory work was to develop and evaluate the packaging and mounting technique for the FO sensors on a GFRP tensile test specimen shown in Figure 5. The specimen was made using a glass cloth DF-1400[7] and Synolite[8] 0288-T5 thixotropic resin system as used on the Royal Australian Navy, Mine Hunter Coastal vessels (RAN, MHC). A 2000-series aluminium (2024-T3) purchased from a local supplier was used to produce end tabs for the specimens. These were bonded to a clean and lightly abraded composite surface on both sides and at both ends using a room-temperature cure, general purpose epoxy resin.

The composite test specimen uses similar materials to those used for the final test on the larger platform. Rather than considering the packaging and mounting of the FO sensors as two

[6] FiberLogix International Limited Watford, Herts UK www.fiberlogix.com
[7] DF-1400® is the product of Colan Australia
[8] Synolite® is the product of DSM Composite Resins AG, Switzerland

separate steps, the approach taken here was to consider it as a single system. Several options were considered, as outlined below.

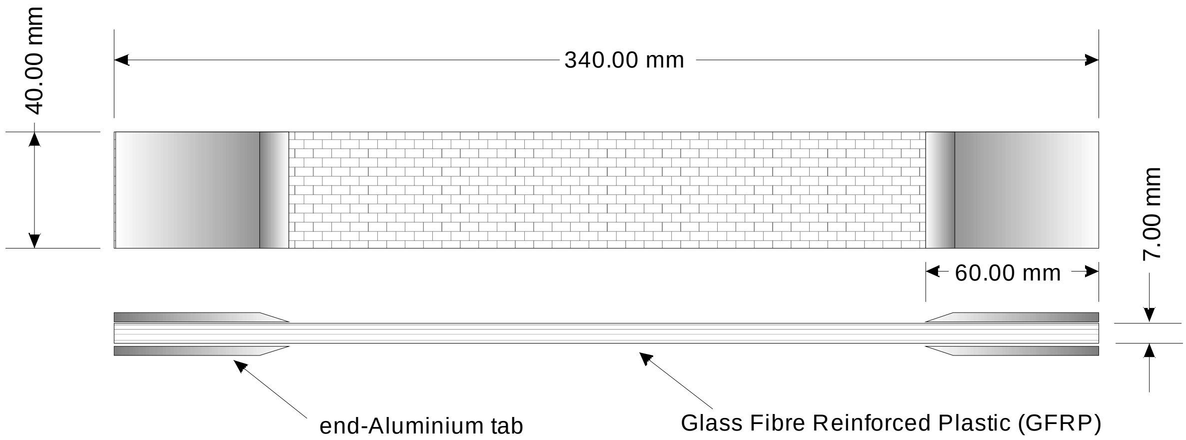

Figure 5: A tensile test specimen used for the development of the FOS packaging and mounting technique.

3.1.1 Option 1

Pressure Sensitive Adhesive (PSA) tapes were considered in the initial trial. The choice of PSA tape was reasonable considering their wide ranging properties and commercial availability at low cost. Furthermore, the tape was envisaged to be useful in transporting the fibre sensors from the laboratory/factory to the site of application. A schematic diagram showing the use of a Kapton[9] tape is shown in Figure 6.

As illustrated, the tape is able to simply cover and secure the fibre in position by adhesive bonding of the tape to the substrate. Contact and adhesion between the fibre and tape occurs for approximately 50% of the fibre perimeter. Therefore, the likely path of the load transfer from the structure to the sensor is as follows: (i) from the structure to the tape backing film through the adhesive layer, (ii) extension or contraction of the tape backing film and (iii) from the tape backing film to the sensor, again through the adhesive layer. The other half of the fibre perimeter (approximately 50%), which is not bonded to the tape or the structure, does not contribute to load transfer mechanism, i.e. the void space indicated in Figure 6 (a).

The results from tensile loading applied to a GFRP specimen fitted with FO sensors, using the Kapton tape, is shown in Figure 6 (b). Three tests were performed, each progressively giving better compliance results in response to improvements in the technique used to apply the tape. Attention to attachment details such as the pressure applied to the tape can significantly increase the contact between the tape and the fibre (which decreases the void space), hence improving strain transfer to the FOS.

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[9] Kapton® is a registered trademark of E.I. DuPont de Nemours Co., product consisting of polyimide film and silicon adhesive designed for high temperature applications, http://www2.dupont.com/Kapton/en_US/

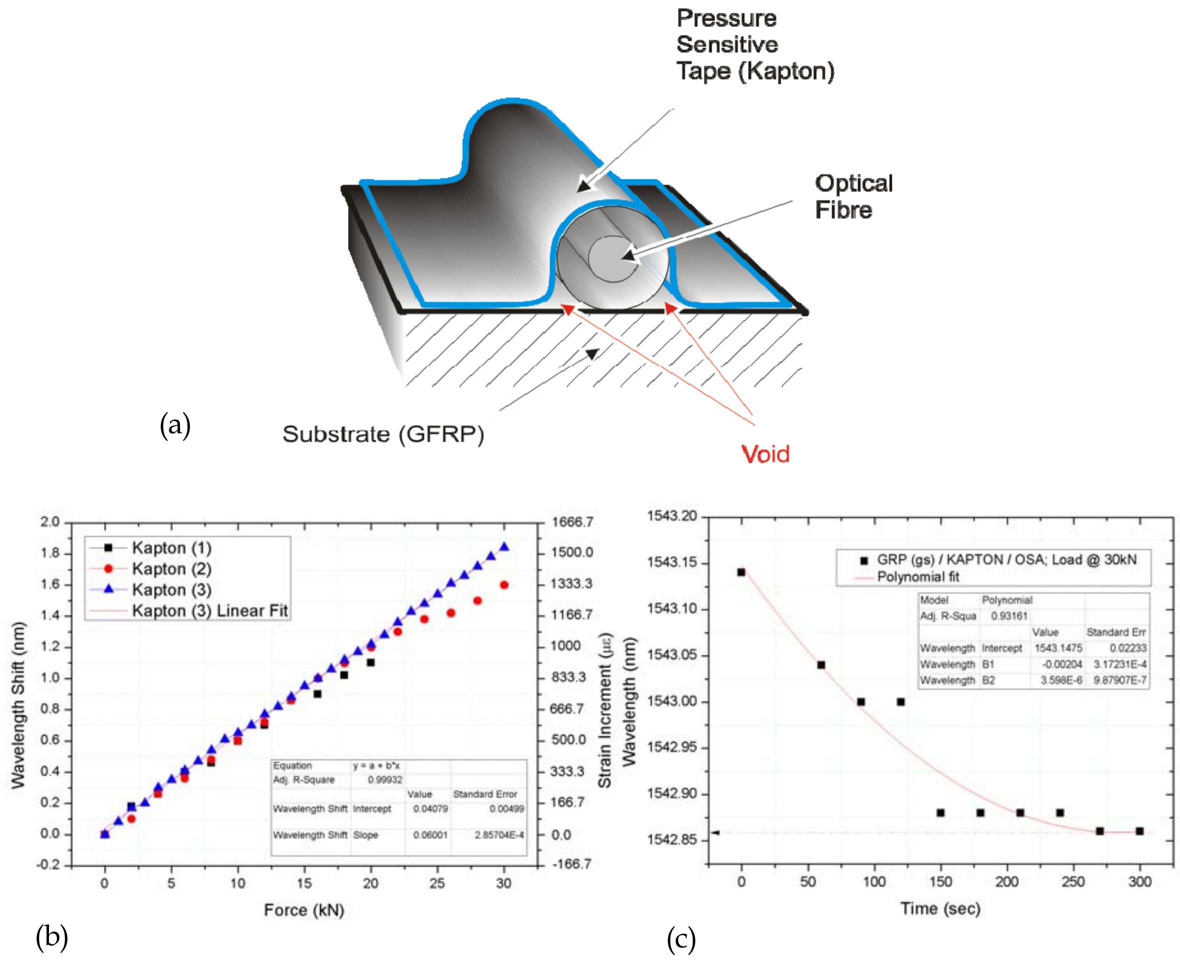

Figure 6: Single fibre sensor / PSA tape system, (a) illustration of tape securing FO sensor(s) to the structure, (b) wavelength shift of the Bragg grating vs. load applied to a specimen fitted with FO sensor and (c) fibre slippage due to creep in the PSA tape.

Additional testing was performed to evaluate the susceptibility of the PSA to strain transfer issues such as creep. This was done by holding the test specimen at a fixed load (30 kN) over a given time period (5 min). The results from this testing are shown in Figure 6 (c) which demonstrate a shift in FBG centre wavelength of approximately 0.28 nm. The gauge factor for a FBG written in standard telecommunications fibre is approximately 1.2 pm/με. Hence this wavelength shift corresponds to a strain relaxation of approximately 230 με as shown in equation (1) below.

$$\text{Signal loss } (\mu\varepsilon) = \frac{Wavelength\_shift\_(pm)}{FGB\_gauge\_factor\_(pm/\mu\varepsilon)} = 280/1.2 = 233.3\ \mu\varepsilon \qquad (1)$$

As shown in this example, the creep would cause an error of approximately 15%.

For SHM applications sensors are typically installed on a structure over a much longer period of time. The use of this and similar PSA tape(s) is not therefore advisable [13]. It may, however, still be useful for attaching FO sensors to a substrate subjected to low amplitude, high frequency dynamic loading provided the tape is applied carefully.

3.1.2 Option 2

The PSA tape method can be improved by filling the void space (~ 50%) with a thermo-set resin as illustrated in Figure 7. To achieve an intimate contact with the structure under all service strain conditions, it was proposed to use a suitable resin system with good penetrating and wicking properties, e.g. low viscosity, and ambient cure. Higher coverage (up to about 75%) of the fibre perimeter with resin can be achieved by simply adding one more fibre placed either side of the active sensor fibre as shown in Figure 7 (b). Those additional fibres could simply be dummy fibres or used if required to provide redundancy to the sensing system.

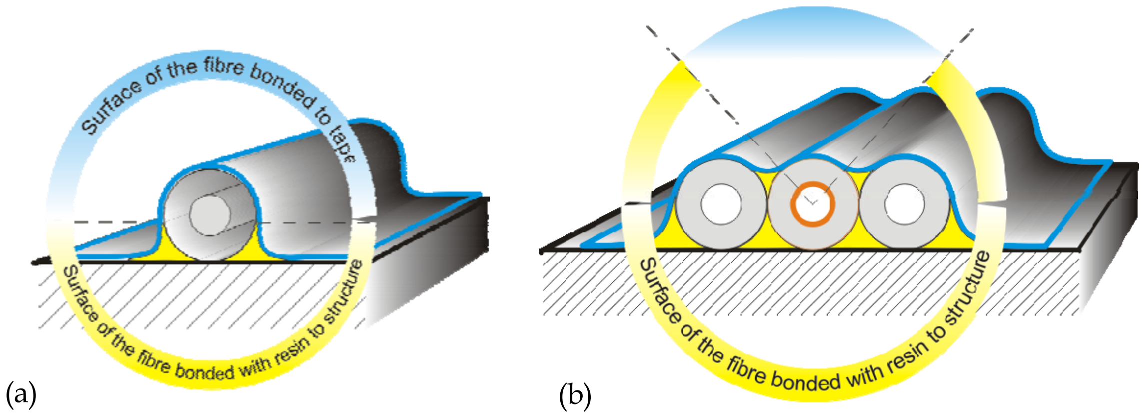

Figure 7: Fibre/PSA tape arrangement with resin bonding (a) Single active fibre, (b) Dummy or redundancy fibres added in parallel to the active sensor fibre.

The method proposed to fill the void space with resin is a vacuum assisted, mini-infusion technique. The tape edges, which run parallel with the fibre and are bonded to the substrate, provide a natural seal; therefore there are only two ends open to the atmosphere. In such a case, resin entry can be facilitated from one end by the use of a partial vacuum applied at the other end of the fibre.

The initial testing was conducted with a single fibre using coloured water rather than resin to test the infusion system. These first experiments were very encouraging, resulting in rapid filling of the void space with water. Similar results were also achieved with subsequent experiments involving a three parallel-fibre arrangement as shown in Figure 8.

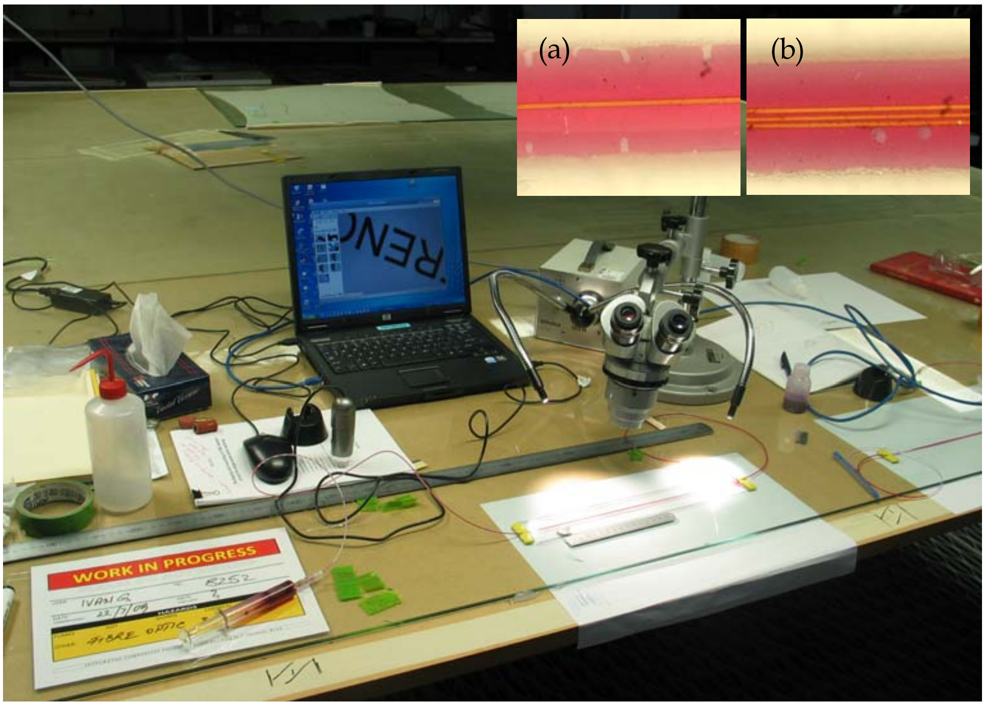

Figure 8: Experimental set-up for water infusion, insets (a & b) show there is no air inclusion (bubbles) around the fibres which demonstrates good wetting.

In the next experiment the water was substituted with resin. The laminating and encapsulating resin selected was the very low viscosity FGI[10] product R180 resin (approx. 110 cP @ 20°C) and the slow acting hardener H180 (viscosity approx. 50 cP @ 20°C). These were mixed as recommended in the proportion 5:1 respectively [14]. Infusion was much slower for the resin than for the water which is about one hundred times less viscous. A partial vacuum created using a syringe was too low to overcome the flow resistance encountered by the resin when entering such a small confined space. It took up to 10 min to advance the resin front by 100 mm, during which time the viscosity had increased due to the initiation of the cure process reducing the resin flow further. Other attempts to work with the same resin system under warmer ambient operating conditions were also unsuccessful.

3.1.3 Option 3

3.1.3.1 Background

To overcome the resistance to resin flow, a mini Vacuum-Assisted Resin Transfer Moulding (VARTM) technique was selected. The VARTM technique has been developed over the last 10 years for application in both commercial and military composite structures [15]. The technique uses only a single sided mould in contrast to Resin Transfer Moulding (RTM) where a double sided mould is used. VARTM is typically a three-step process including the lay-up of reinforcing fibre pre-form[11], pre-form impregnation with resin, and ambient or elevated temperature resin cure.

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[10] FGI – Fiber Glass International, Australia, http://www.fgi.com.au/

[11] A pre-form in this context is a vacuum consolidated stack of fibreglass plies in dry form ready for resin infusion.

A GFRP test specimen with the various components used in the mini-VARTM process is shown in Figure 9. The GFRP surface preparation comprised light abrasion, removal of loose particles followed by degreasing with acetone.

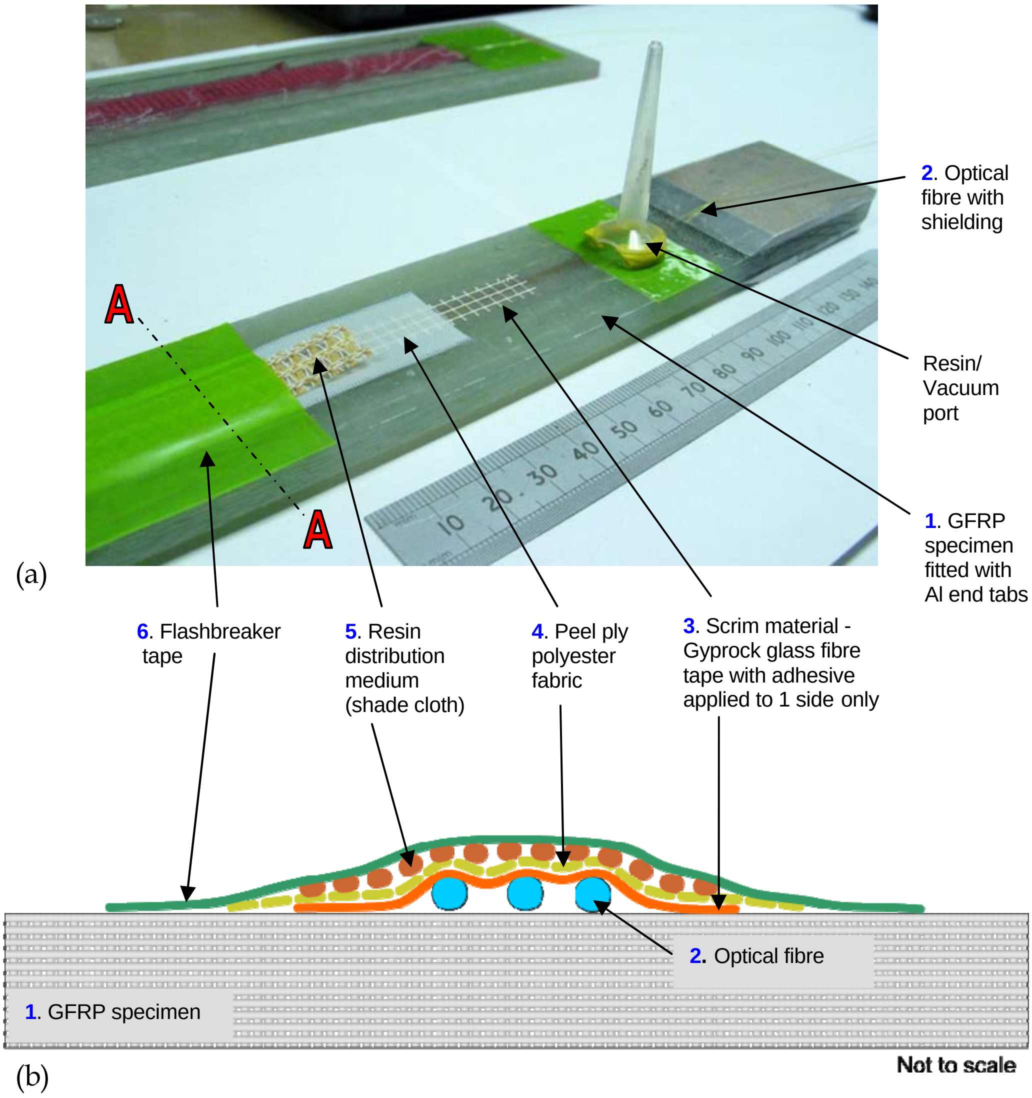

Figure 9: Typical lay-up for resin infusion and bonding of FO sensors to GFRP test specimen (lay-up order from bottom to top), (a) all materials used in mini-VARTM and (b) cross-sectional view at point A-A. Note, after resin infusion and cure the layers 4, 5 & 6 are removed.

More detailed information about VARTM layers shown above and the resin system for packaging and mounting is given below.

3.1.3.2 VARTM Layers

The first layer of the VARTM system is a pressure sensitive, self-adhesive tape (Gyprock[12] Easytape) used widely in the jointing of Gyprock plasterboard walls and ceilings. The tape (shown enlarged in Figure 10) is very thin and has an open structure made of glass fibre to which adhesive is applied only on one side. This widely available, cheap product was found very useful for several reasons:

- The tape readily adheres to various clean surfaces.
- The tape prevents fibre movement after overlaying. Adhesive sticks to both the fibres and the substrate.
- After bonding with resin, the glass fibre tape provides physical protection as it remains as an integral part of the sensor system.
- For transport purposes the tape can be rolled-up with the optical fibre(s) attached and at the destination unrolled with no damage to the FO sensors.
- The rigidity of the glass fibre construction provides protection to optical fibres from being over-stressed during the rolling-up process in preparation for transport (see Section 4.1).

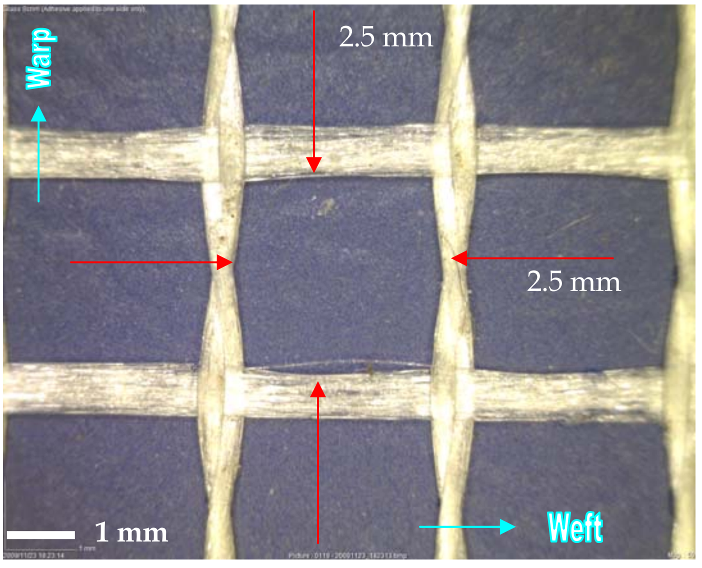

Figure 10: Gyprock Easytape – pressure sensitive product with adhesive applied to one side of its glass fibre construction.

The second layer is a peel ply which is generally used in VARTM for separation of the resin distribution media from the specimen once the resin cures. A drapable polyester fabric (Release ply F from Airtech USA [16]) of relatively high strength and very permeable to resin was used, see Figure 11.

[12] Gyprock™ is a Trade Mark of CSR Limited, Australia, http://www.gyprock.com.au/

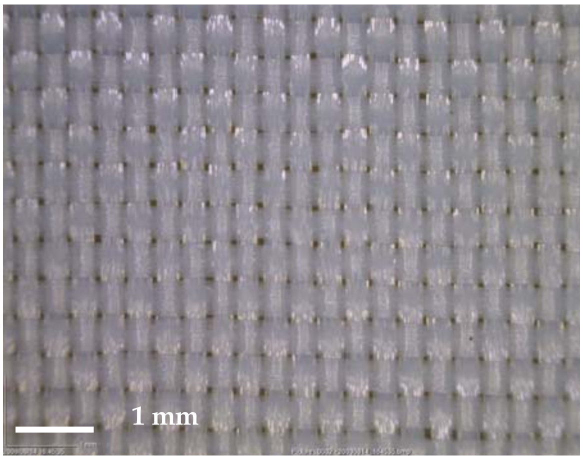

Figure 11: Release Ply F from Airtech USA [16].

The third layer of the VARTM lay-up acts as the resin distribution medium. The material utilised was an inexpensive shade cloth available from a local hardware supplier, see Figure 12. The shade cloth material has a knitted structure with approximately 50% open volume and was found suitable for all small-scale work described in this report.

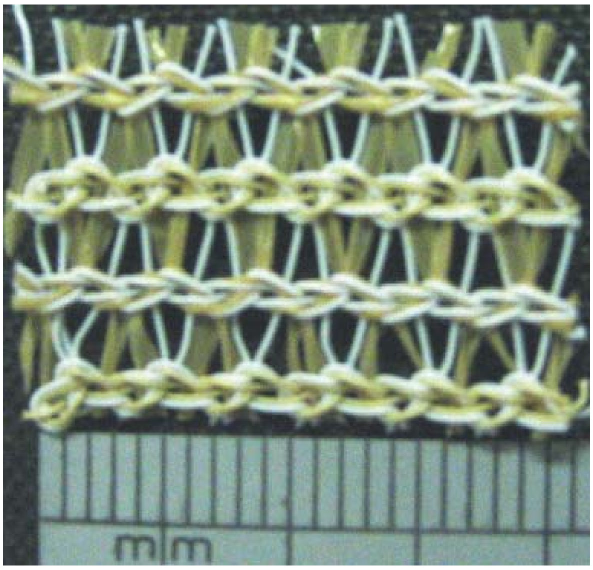

Figure 12: Shade cloth material used in the resin infusion method for small-scale work test specimens.

3.1.3.3 Resin System for Packaging and Mounting

The choice of a resin system for this task was essentially limited to low viscosity thermoset systems. While low viscosity is required to achieve good wetting and adhesion to a substrate in order to optimise the strength of a secondary bond, the thermosets also provide bonds with high strength and, unlike thermoplastic systems, do not show a tendency to creep. This is especially important when considering both small and larger strains generated through structure-borne vibrations and manoeuvre loading. Ideally, all the strain experienced by the structure should be fully transferred to the fibre which can be achieved when FO sensors are in intimate contact with the structure, i.e. no layers of other materials are present between the structure and the FO sensor.

The choices for a potential resin system for this task were wide and varied. Many commercially-available adhesives were sourced and the candidate list is provided in Appendix A. The final selection was based on availability, performance and cost, from Fibreglass International (FGI), Resin: R180, Hardener: H180 slow[13] [14].

Generally, the parameters affecting the resin flow velocity under a vacuum are; (i) the resin viscosity; (ii) the vacuum pressure level and (iii) the permeability of the preform. In this case the resin viscosity was low (i.e. 110 cP @ 20°C), the reduction of atmospheric pressure needed was minimal (i.e. 5 kPa) and the permeability of the 2-ply preform (scrim material and optical fibres) was negligible. Thus the infusion process was completed in less than 5 mins which is well within the resin working time (the gel-free time for this resin at ambient is around 25–30 mins). For the purpose of mechanical testing, a total of 5 specimens were produced. Of those, three test specimens had 3 optical fibres bonded and the remaining two had only 1 optical fibre bonded to the test specimen as outlined in Section 3.1.2. These options were explored to determine if there are any effects on strain measurements. Prior to testing, all 5 specimens were heated to 40°C for 35 hours in order to post-cure the resin. A small amount of red dye was added to the resin to enhance its visibility for inspection purposes.

In order to determine the effect of resin encapsulation on the FBG following resin cure and postcure, an Optical Spectrum Analyser (OSA) ANRITSU MS 9710 C was used to record the reflection spectra from the FBGs before and after attachment as shown in Figure 13.

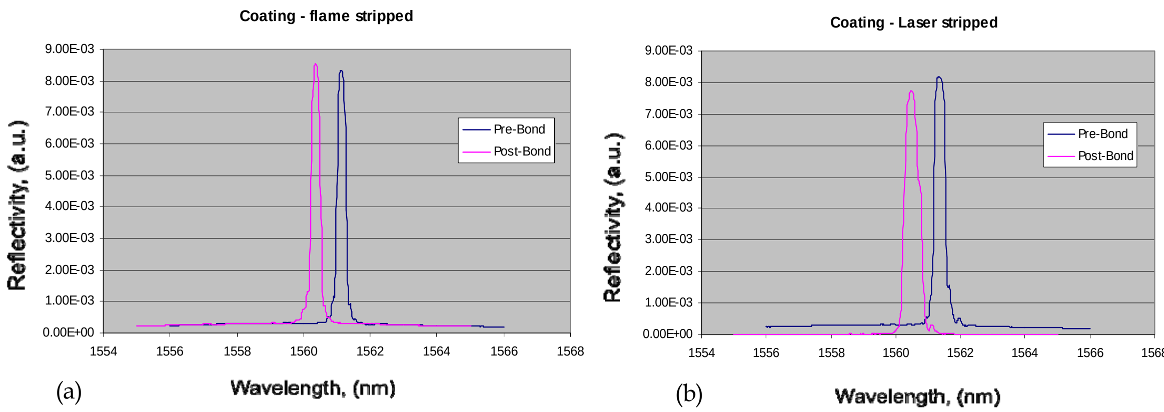

Figure 13: Effect of resin encapsulation on central peak wavelength for fibre with (a) flame stripped coating and (b) laser stripped coating.

The observed shift from pre- to post-bond wavelength of the central peak position was noticed for all specimens, irrespective of the method used to strip the fibre coating before writing the FBG grating. The lower peak-wavelength after resin encapsulation indicates fibre compression which is to be expected due to resin shrinkage resulting from resin cross-linking. The cross-

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13 H180 slow® is a product of Fiber Glass International (FGI) Australia, http://www.fgi.com.au/files/images/stories/pdfs/products/resins/Epoxies.pdf

linking chemistry of a resin usually produces a reduction in volume which is recognised as resin shrinkage. Further very minimal fibre compression was observed after resin post-cure.

The quality of resin wetting and encapsulation of the fibres was examined with a Scanning Electron Microscope (SEM). A cross-section indicating the thickness of the resin infused layer that contains an optical fibre is shown in Figure 14.

The encapsulating layer shown in Figure 14 was produced on a release film; therefore, the bottom surface indicated in Figure 14 corresponds to the resin layer interface bonded to the GFRP specimen. The optical fibre is at the bottom of this layer and in reality 'sits' on the surface of a specimen. There are no additional materials between the fibre and the specimen thus, the strain in the specimen is efficiently transferred to the fibre optic sensor. Theoretically, there should be no slippage or deformation of the fibre under load since the entire fibre perimeter is encapsulated in a relatively rigid epoxy resin.

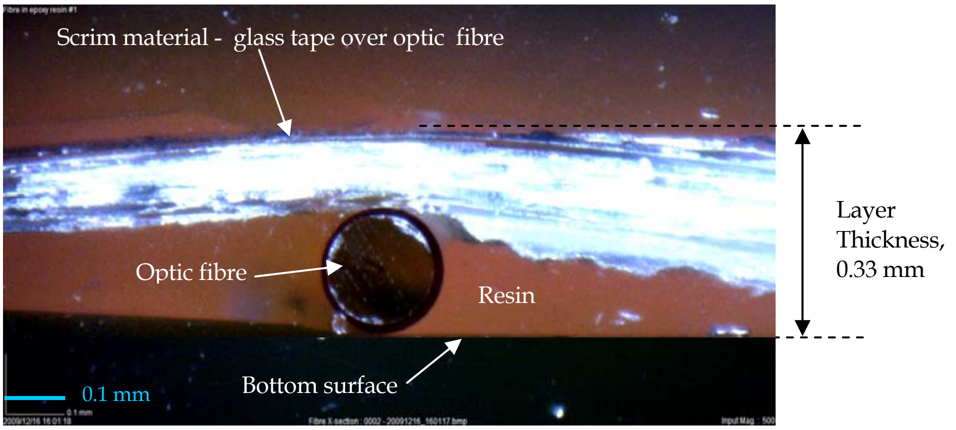

Figure 14: A SEM micrograph of the cross-section of the VARTM attached OF sensor.

Each active fibre was fusion-spliced to a jacketed fibre patch cord which was connected to the light source and detector. To protect the egress point of the fibre from the VARTM packaging, the splice and a small length of the jacketed fibre was also infused with resin. The integrity of both the fibre and the splice was assessed after resin encapsulation using a fibre-coupled visible (632 nm) laser diode source, see Figure 15. Any damage to the fibre will be indicated by visible laser scatter at the point of damage.

A total of 5 specimens were instrumented with FBG sensors. After resin infusion, 1 of the 5 specimens failed as indicated by the laser light scatter at the fusion splice in Figure 15 (b), leaving only 4 specimens for mechanical testing.

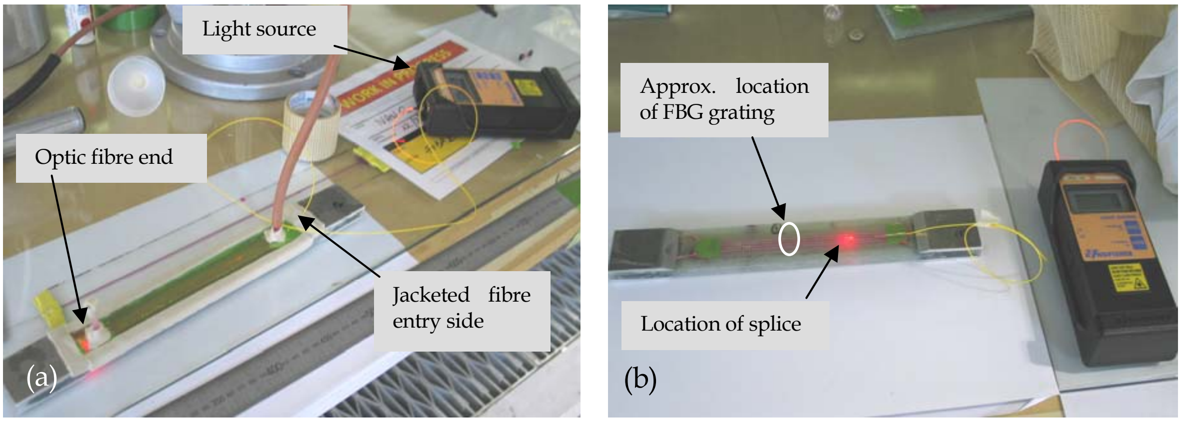

Figure 15: Light transmission test through resin encapsulated fibre, (a) scattered light seen at the end of the fibre, (b) light scatters at the splice indicating failure to transmit light.

3.2 Mechanical Test Results

A set of mechanical tests were performed to assess the proposed packaging and mounting technique (Option 3) for the FBG sensors. Each test specimen fabricated for this purpose was also instrumented with a standard electrical resistance strain gauge to provide an independent measure of strain.

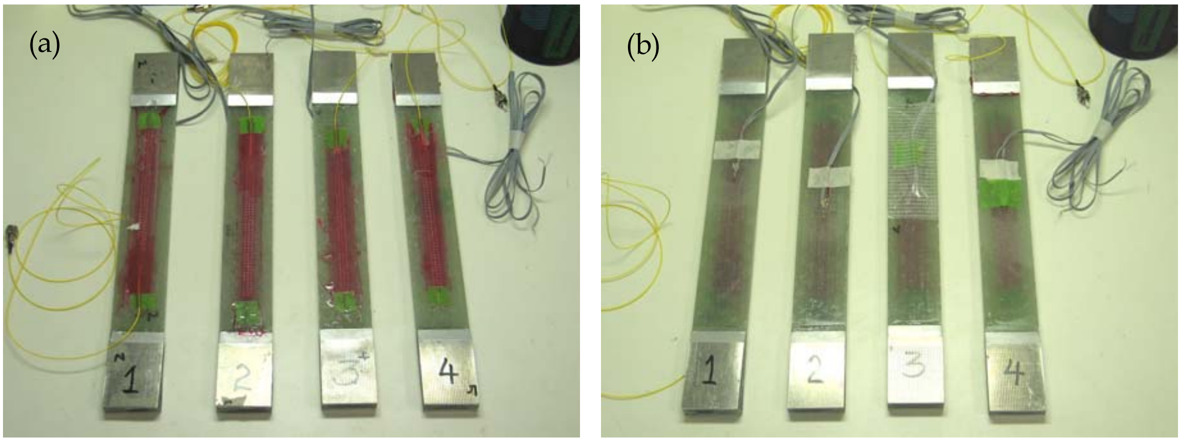

Figure 16: Mechanical test specimens with (a) mounted FO sensors and (b) bonded strain gauge on opposite side.

The initial testing focused on assessing the following properties:

(i.) *Linearity* of the sensor output with respect to load.
(ii.) *Hysteresis* in the sensor response.
(iii.) *Sensitivity* or *responsivity* of the sensor system.
(iv.) *Creep* of the encapsulating resin.

The remaining 4 test specimens (shown in Figure 16) were evaluated under identical test conditions following the same test regime. The specimens were loaded in tension at 2 kN intervals from 0 to 30 kN (0 to ~5500 με) using a servo-hydraulic MTS testing machine fitted with a 50 kN load cell and an MTS Micro-console controller 458.20. The strains measured by the electrical resistance gauges were recorded using a DSTO MK II Strain Gauge conditioner.

Unfortunately, further fibre failures in the splice grating region occurred in 3 specimens (#1, #2 & #4 in Figure 16) at loads ranging from 20 to about 28 kN (3600 to ~5100 με). For example, the optical fibre shown in Figure 17 appears to have developed multiple failures (fractures) in the splice and the grating region. There were 4 areas in the optical fibre where light scattering was observed, although it is not completely clear what mechanism of failure is responsible for this effect. These fractures appeared incrementally at the applied loads of 20 kN, 22 kN and 28 kN.

Although the fibres themselves failed at moderate strain levels, these failures occurred at the splice and FBG sensor regions in the fibre where the coating has been stripped. These unprotected regions of the fibre are well-recognised weak points. The VARTM packaging appeared intact for all the specimens at the completion of the tensile testing. In future testing where the reliability of the fibres themselves will be investigated, FBGs written directly in a draw-tower [14] prior to coating will be used to avoid fibre failures caused by the fibre stripping process.

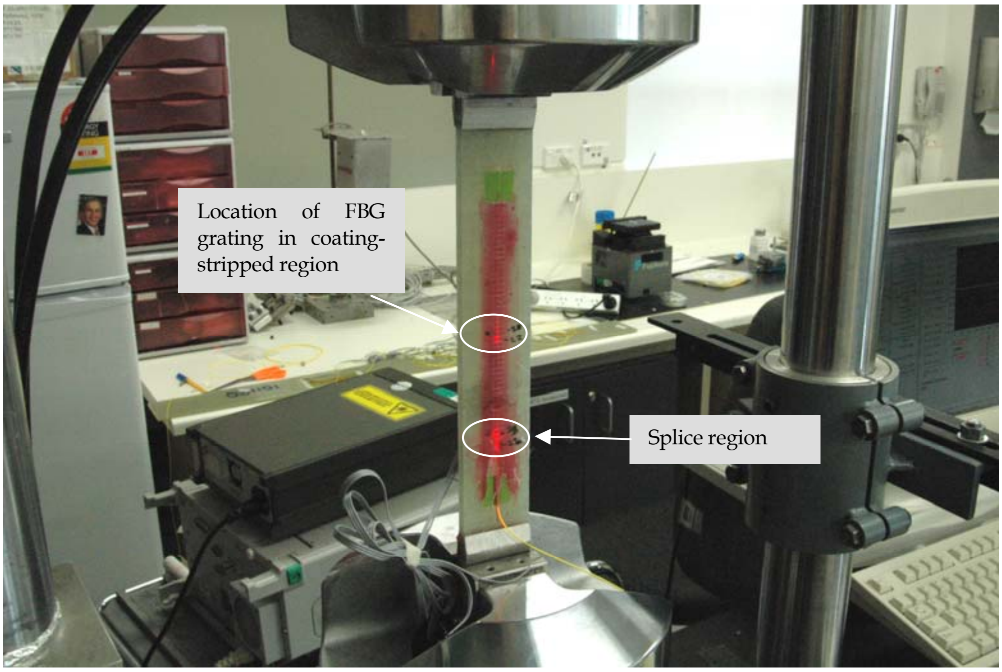

Figure 17: Test specimen showing multiple fibre fractures due to application of tensile load.

The remaining intact specimen (#3) was repeatedly loaded to 30 kN without the optical fibre experiencing a failure, enabling an assessment of the four properties mentioned earlier. The results are shown in Figure 18.

[14] FBGS Technologies GmbH, http://www.fbgs-technologies.com/

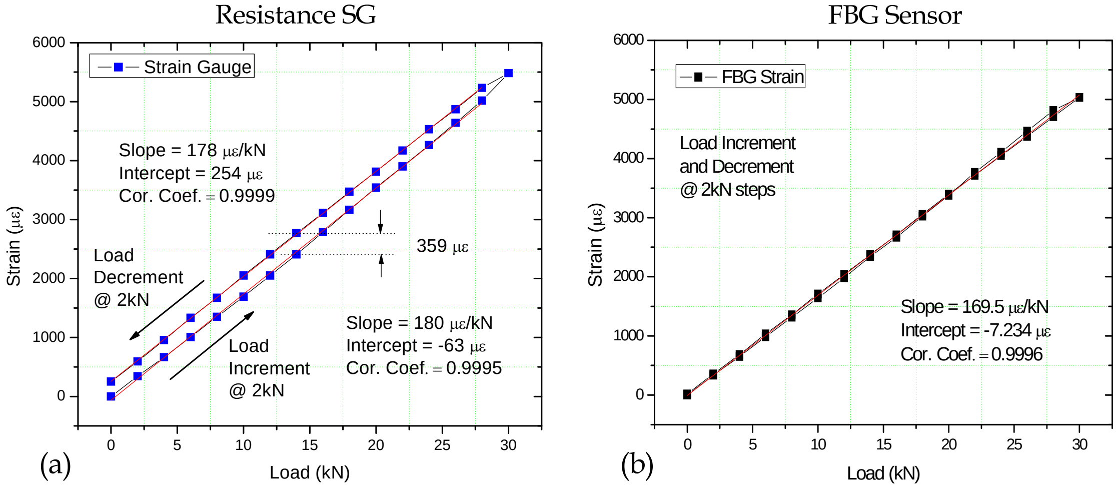

Figure 18: Strain response from specimen #3 - Sensor output (a) resistance strain gauge, (b) FBG sensor.

(i) The *linearity* of sensor output is shown in Figure 18. Both sensors showed only a small deviation from linear response across a 30 kN. In both case the linear fit gave a correlation coefficient >0.999.

(ii) A test for *hysteresis* was performed by incrementally loading the specimen from 0–30 kN in steps of 2 kN, followed by reversal of this procedure at the same rate back to 0 kN load. This load range was chosen to induce the maximum strain range that might typically be seen in service.

The SG data show a typical hysteresis loop indicating either a possible permanent 'set' acquired by the gauge element or some problems with the bonding of the gauge [17]. As shown in Figure 18(a), the hysteresis error, being the maximum separation between the loading and unloading strain traces is about 360 µε. Further work may be needed to investigate this anomaly.

In contrast, the response of the FBG sensor showed no such hysteresis.

(iii) The *sensitivity* or *responsivity* of the two sensors is similar with the electrical strain gauge exhibiting a strain sensitivity of between 178 and 180 µε /kN and the FBG showing a slightly lower sensitivity of 169.5 µε kN. This small discrepancy may be explained by different bond-line thicknesses or possibly degradation or deformation in one of the sensing materials in the electrical foil gauges under the higher strains as suggested by the hysteresis and creep data.

(iv) *Creep* describes the tendency of a material to undergo permanent deformation to relieve stresses; therefore creep is not regarded as a failure mode, but rather a deformation mechanism. The rate at which this deformation takes place is dependent on material properties, exposure time, exposure temperature and the applied load (stress). In this work only two variables were considered; the elapsed time and the load sufficiently high to impart considerable strain on the bonding resin. The specimen was loaded to 15 and 20 kN and held at each load for a 10 minute period. Other variables were assumed to remain relatively constant during the course of the measurement period (10 minutes). The results of these tests are given in Table 1. The strain calculations for the FBG are made using the assumption of a standard gauge factor of 1.2 pm/με given in Sec. 3.1.1.

Table 1: Creep test results for bonded sensors.

LOAD (kN)	TIME (min)	SG (με)	FBG (nm)
15	0	2589	1544.97
	10	2733	1545.02
		Δε = 144 (5.6%)	Δε = 42 (1.6%)
20	0	3471	1545.90
	10	3632	1545.93
		Δε = 161 (4.6%)	Δε= 25 (0.5%)

Further information was obtained by analysis of the FBG reflection profiles for which the change in wavelength is within the detection limit of the OSA. The spectra were of similar shape and position before and after the creep test (see Figure 19) indicating that there is no residual strain in the FBG.

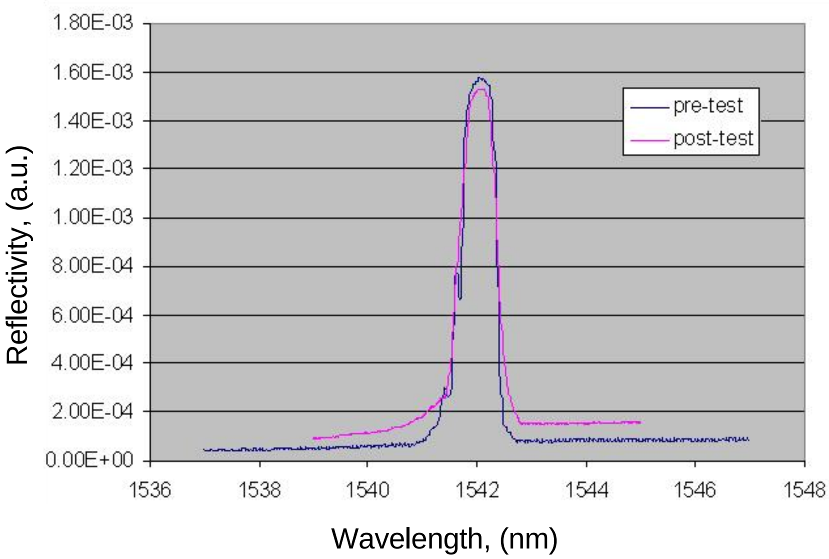

Figure 19: FBG central peak position before and after creep.

The SG data in Table 1 confirms that creep occurred somewhere in the sensor system. A strain increase of the order of about 5% was detected after each test. Since this value falls within the SG standard error range (± 5%) it is difficult to make any judgement on the source or magnitude of creep without additional work such as extending the testing time at several set-load ranges. Linking this observation with the hysteresis shown in Figure 18(a) suggests possible problems with the bonding of this sensor.

4. Large-Scale Applications

The mini-VARTM technique described in Sec. 3.1 for small-scale infusion requires some modification for larger scale applications. These variations are discussed below.

4.1 Preparation of Long FBG Sensor Arrays for Transportation

The handling and transportation of a large number of sensors are issues that need to be considered for large scale applications since the potential for damage to occur to fibres during handling and transport are high. SHM of large structures may require a multitude of long fibres with sensor arrays written on them as shown in Figure 3. Production of these sensors on such a large scale involves significant human and financial resources. Beside the cost, the fragility of these small diameter glass-core fibres, with discrete buffer stripped regions and which may be up to 10 m long is a real issue, hence the handling (e.g. preparation for transport, delivery to the site and location on a structure) requires careful consideration. For example, an exceptionally tedious task would be to manage long fibres on a large vertical or overhead application in preparation for resin bonding.

To address those concerns, the approach taken in this work was to minimise fibre handling by using the *Gyprock Easytape* (Figure 10) as a carrier material for the fibre arrays. This inexpensive and widely available tape was found ideal for the job. The tape can be used to hold down and 'stick' in position the optical fibres while preparations are made for resin infusion. Afterwards, it remains a part of the sensing system providing mechanical protection to the FBG sensors. In addition, the tape's glass-fibre construction prevents the optical fibres from being overstretched and damaged during the winding-up process described below.

Some of the aspects of managing long fibres in preparation for large-scale sensor application are shown schematically in Figure 20. This work can essentially be divided into two separate operations. One is to make preparations for fibre transport at the sensor production site, Figure 20(a). The other involves activities at the application site where the sensors are attached to the structure, Figure 20(b).

The activities shown in Figure 20(a) are likely to occur at the fibre sensor production site, i.e. factory, where clean and large flat surfaces are readily available. The procedure is simple and should involve the following steps:

(i.) Alignment of fibre configuration(s) on a table. One, two or more fibres can be considered (i.e. an active sensor fibre with or without redundancy).

(ii.) Overlaying fibres with glass tape (*Gyprock Easytape)* which adheres to both the table surface and the fibres. The tape provides only weak adhesion but it is sufficient to retain the fibre in position, and the tape can be easily peeled from the table.

(iii.) Utilising a suitable cylindrical tool (mandrel) and fixing the start of the glass tape on its surface as shown in Figure 20(a).

(iv.) Rolling the tool at the appropriate speed to pick-up all the tape off the table surface (fibres are stuck to the tape's adhesive side). Cover the tool and the tape using a suitable protective film in preparation for transport. (Note, after the wrapping step the tape's adhesive side is now exposed and will securely hold the protective plastic film in place).

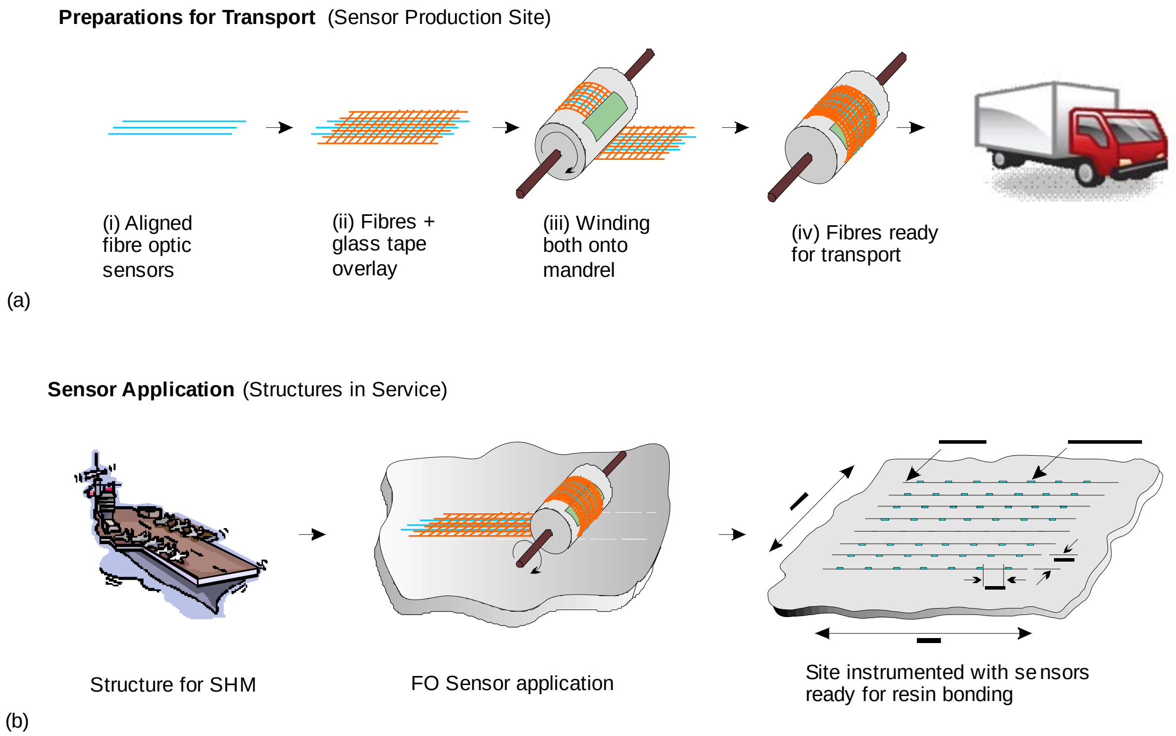

Figure 20: Managing long fibre sensors (a) preparations at the sensor production site, (b) sensor application at the structure site.

In the process of preparing the FO sensors for transport there are several issues relating to points (iii) and (iv) above that need further consideration.

Referring to (iii) above, the diameter of the cylindrical tool selected to wrap around the fibres should be larger than the minimum bending radius specified by the fibre manufacturer, as excessive bending may cause some damage to the fibre. In this case the diameter chosen for the mandrel was 180 mm which is also a convenient size for storage and transport and far exceeds the minimum bend radius specified for this fibre type (27 mm).

In point (iv), the example presented assumed the optical fibre was applied in a straight line. If the tool used for this purpose cannot ensure straight-line tape pick-up, a long guide with a straight edge may be used instead during the wrapping process to align the tool with the fibre. Otherwise, any misalignment in the wrapping process may translate to the structure during the tape unwrapping procedure.

Additionally, there was some concern that the thickness of the fibres might be too large with respect to tape and would affect the tape overlap uniformity causing it to distort from the position set-up on the table. The problem can be largely avoided by aligning the optical fibre as in Figure 21. The optical fibres are stuck only to the fibres in the weft direction which are made into a flat ribbon consisting of small glass filaments (Gyprock Easytape, Figure 10). In the warp direction, two strands are twisted during the manufacture and every 2.5 mm a weft glass ribbon is inserted and held in place. A cross-section of this weave including a correctly scaled optical fibre is shown in Figure 21. The average thickness of the tape is around 250 μm, while that of the optical fibre is approximately 145 μm (FiberLogix, Figure 4) meaning that the optical fibre protrudes only marginally above the tape profile. In practice, after winding-up and unwinding steps, there was no observed misalignment of the tape or optical fibre for the large-scale simulations shown in Figure 22.

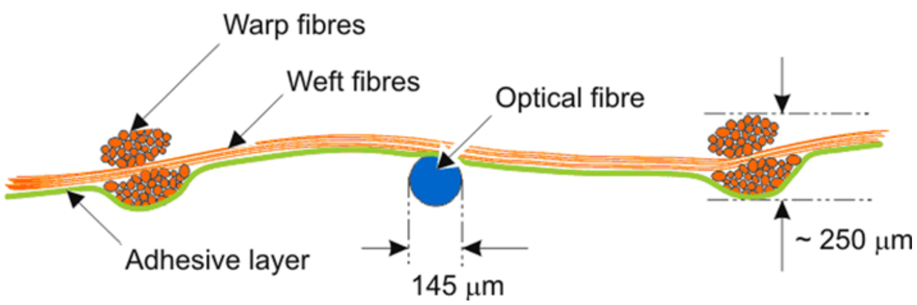

Figure 21: Schematic diagram of cross-section through Gyprock Easytape with attached optical fibre.

A collage of pictures taken to demonstrate the main steps involved in preparing the fibre for transport is shown in Figure 22. Three polyimide-coated optical fibres, each 3.5 metre long, are shown in this example. In Figure 22(a) the three fibres are laid on the work surface parallel to one another and the self adhesive Gyprock Easy tape is overlaid on top of them. In Figure 22(b) the fibres (adhered to the tape) are rolled-up onto the mandrel. Then in Figure 22(c) the wound

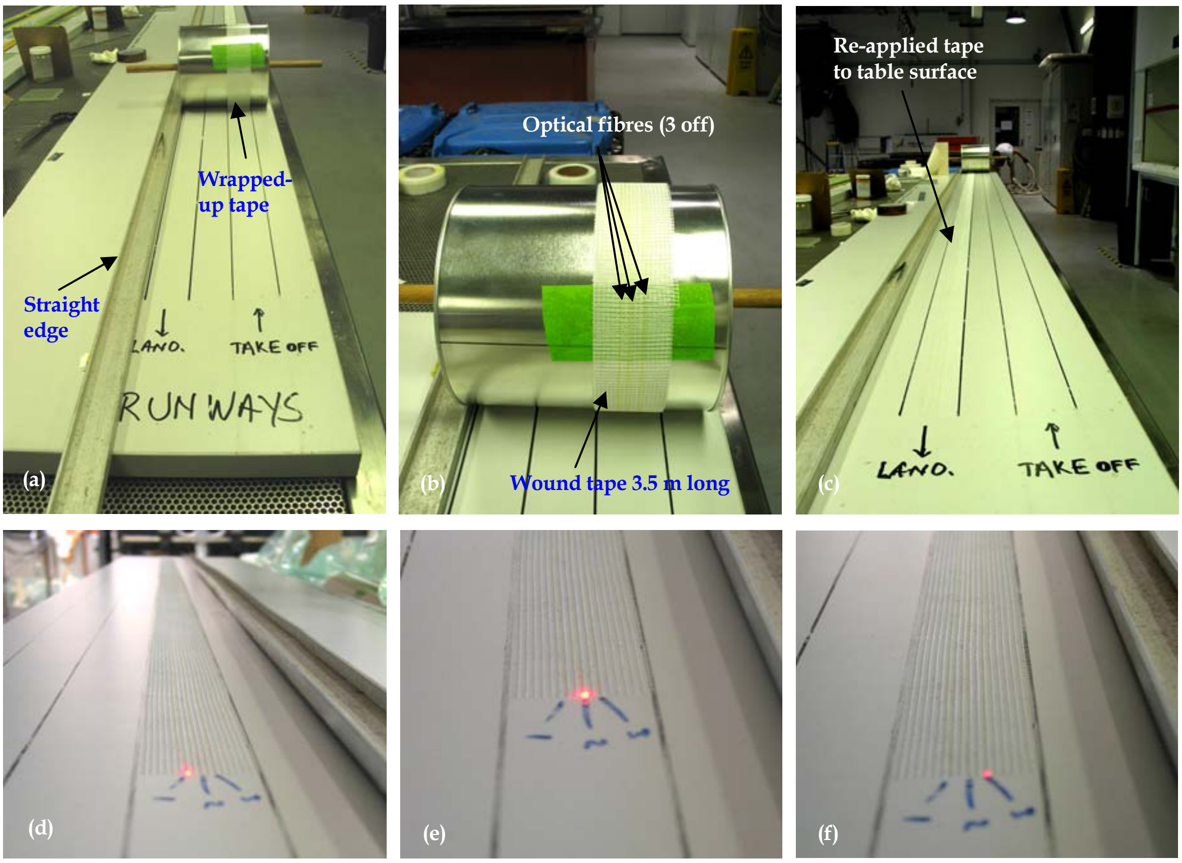

Figure 22: Laboratory simulation of long fibre transport (a) wrapping tape onto mandrel, (b) total length picked-up from table, (c) tape re-applied to adjoining surface, (d) light transmission test for fibre 1, (e) fibre 2 and (f) fibre 3.

tape is transferred to a different section of the work bench, to simulate the application of the fibre arrays at the application site, and simply rolled-out to complete the process.

Subsequently, all three fibres were checked for possible damage using a visible laser diode source. The outcome of these tests indicated no failures in light transmission for any of the three fibres. It should be noted, none of these fibres contained FBG sensors, and therefore no areas of stripped fibre coating were present. The same procedure can be used in future checks when using fibres containing FBG sensors.

4.2 Mounting of Fibres – The Effect of Size and Time

In order to accommodate an increase in the size of the structural application, the mini-VARTM process (Sec. 3.1.3) was adjusted by extending the fibre bonding length from about 200 mm to approximately 3,300 mm. This change has an impact on the time needed to complete the infusion which, in turn, relates to the required gel-free time of the resin system. Initially, several experiments were conducted to establish the maximum distance the resin can cover before the onset of resin gelling while using the same materials as in mini-VARTM technique (see Figure 9). A summary of the results from these tests is given in Figure 23.

The first experiment proved that the resistance to resin flow through the original resin distribution medium (shade cloth, Figure 12) was far too great. By adding another layer of shade cloth in the second trial, the resin speed and distance increased somewhat but not sufficiently. The time needed to cover just 500 mm was in excess of 10 minutes which means that on a warmer day (25–30°C) when bonding the sensors on-site; the gel-free time would be close to expiring.

In order to further increase the resin flow for large-scale application, a more open structure using a shade screen made from High Density Polyethylene (HDPE) was used, see Figure 23 (top inset) and Figure 24(a). Under full vacuum, both the resin infusion speed and the distance were acceptable. In just 6 minutes the resin reached a distance of 1,400 mm before a second resin infusion point (RIP) was introduced in the fourth experiment which increased this distance to over 3 metres. Note, in multi-RIP system the resin is pre-mixed with the curing agent just before infusion so the consecutive resin mixes for RIP 1, 2, … n always remain well within the gel-time (max. handling time 25–30 min @ 25°C).

Thus, by changing to another resin distribution medium from that used in the mini-VARTM technique and adding another resin injection point, a large scale packaging and surface mounting system for multi array, fibre sensors becomes feasible. An additional advantage is the flexibility of this method. The number of resin injection points can simply be added, each approximately 1,400 mm apart, to cover larger distances. This slight modification of the technique from mini-VARTM to that involving the mounting of a large scale sensor arrays has no effect on resin infusion quality or resin chemistry. Therefore, the sensor performance in service including sensor output is not expected to deviate from that described earlier in this report.

In addition, another resin distribution medium, i.e. Teflon-coated peel ply with more open structure, was trialled for large-scale work. A photograph of this peel-ply is shown in Figure 24(b) [18].

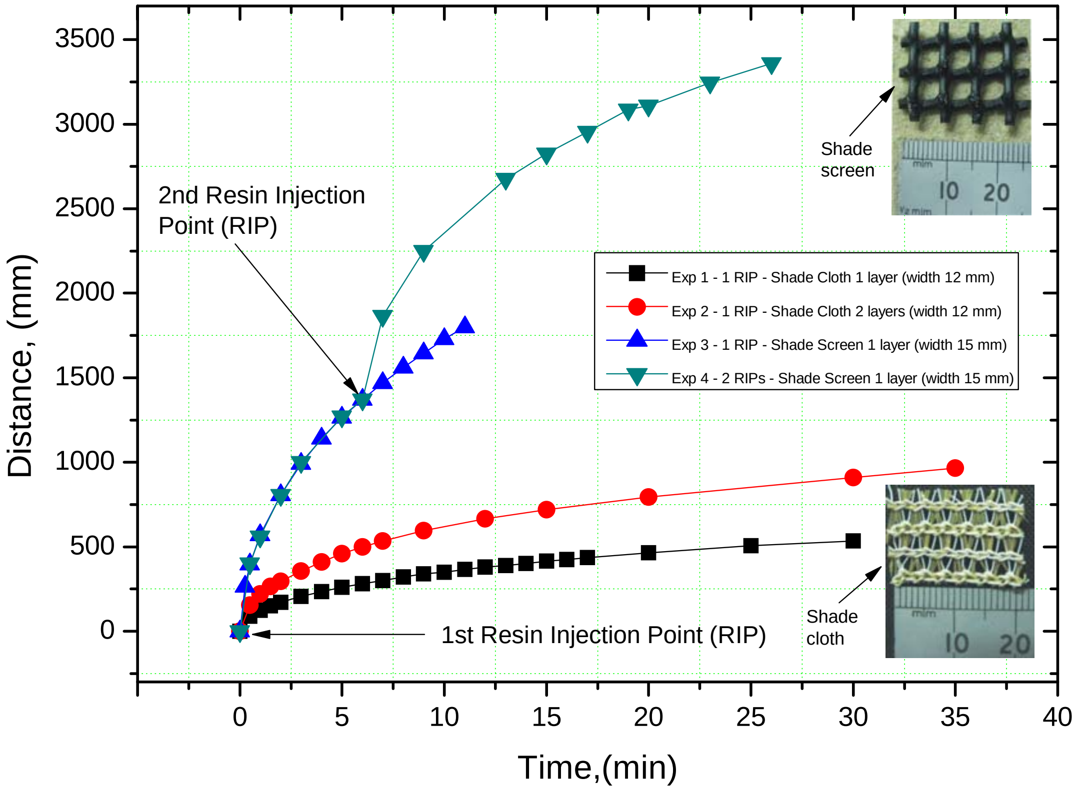

Figure 23: Resin infusion experiments for large-scale surface mounting of fibre optic sensors. In Exp. 1 (■) the resin infusion reached the distance of about 500 mm over 30 min (1 layer of shade cloth used), in Exp. 2 (●) the resin infusion increased to about 1000 mm in 35 min (2 layers of shade cloth used), in Exp. 3 (▲) a much faster resin infusion rate was achieved, i.e. 1,750 mm in 12 min and in Exp. 4 (▼) the use of 2nd resin injection point extended the distance to over 3,300 mm in about 25 min (1 layer of shade screen used in Exp. 3 &4).

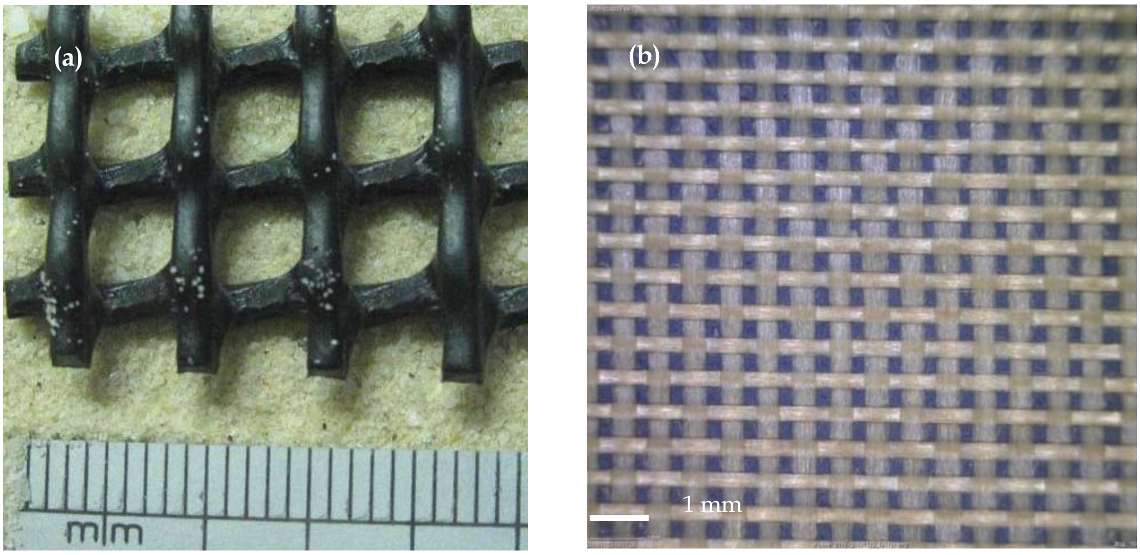

Figure 24: New materials for large-scale work, (a) shade screen HDPE and (b) Airtech : Release Ease 234TFP (Teflon coated Fiberglass fabric).

Some graphical evidence showing the evolution of the large scale lay-up process is given in Figure 25.

Following resin infusion, light transmission tests were conducted on the three optical fibres, see Figure 26. The purpose of the test was to establish the integrity of fibres especially in stripped-coating regions, e.g. splices, after exposure to vacuum pressure. The results of these tests showed that one fibre failed in the splice region, Figure 26(c).

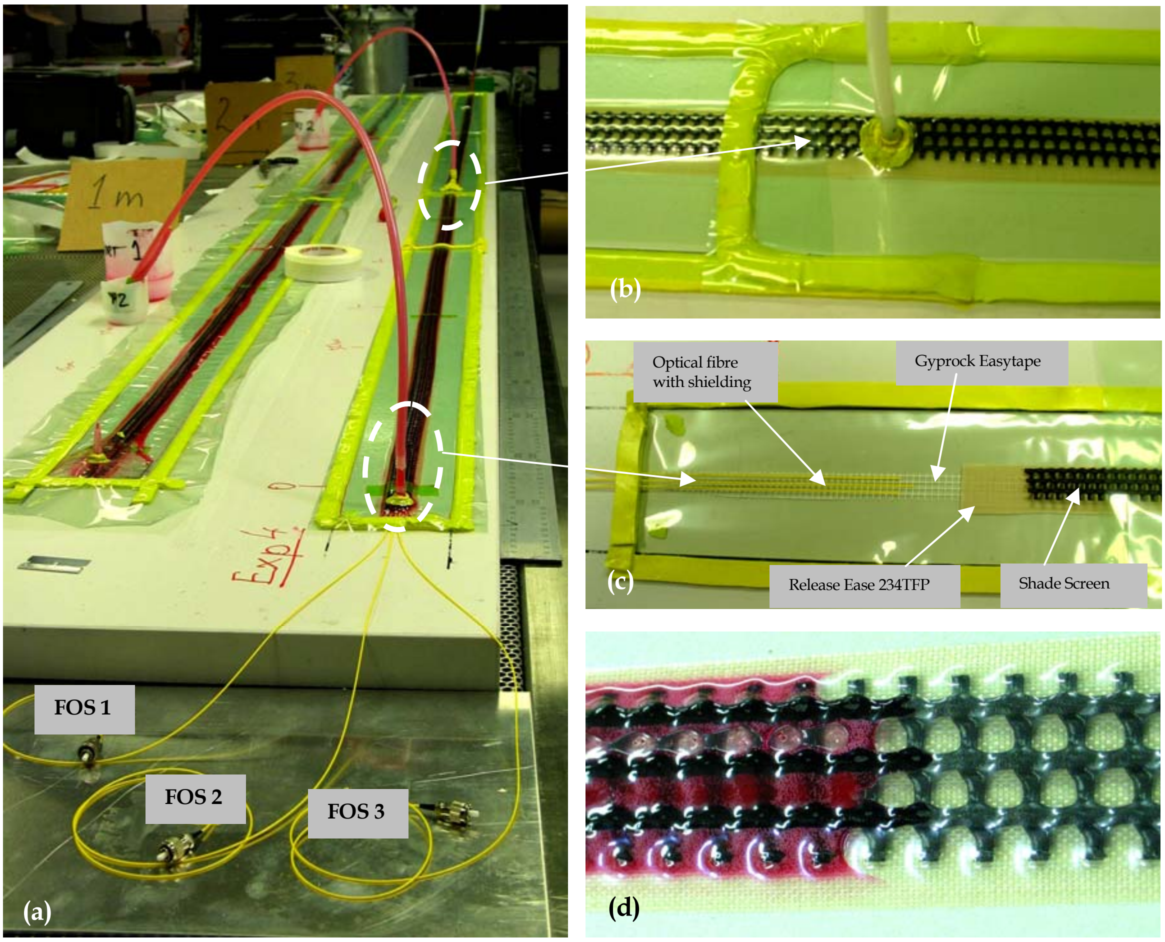

Figure 25: Large-scale simulation (a) experiment 3 & 4, (b) 2nd injection point detail, (c) components lay-up, (d) close-up of advancing resin front

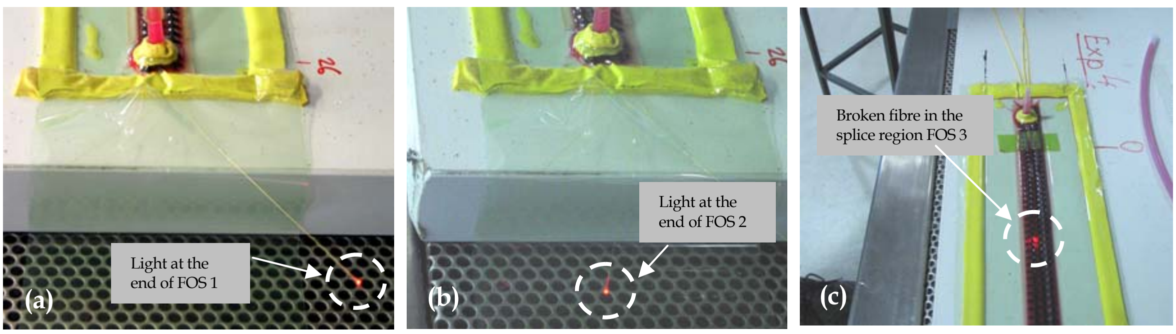

Figure 26: Optical transmission test (a) FOS 1 = OK, (b) FOS 2 = OK, (c) FOS 3 = Failed.

4.3 Factors to Consider for Onsite Application

The site conditions under which the fibre sensor arrays are installed can vary significantly from day-to-day but provisions for sudden daily changes in the weather (wind, rain, snow, heat/cold, etc.) should also be considered. For this reason a well planned schedule of activities is essential to cut down the time needed to complete the job.
Table 2 provides a break-down list of suggested major activities on board the vessel including the approximate time needed for each and comments to note. This list of work assumes work on-site only. It excludes all laboratory/factory preparation of sensors and acquisition of materials, equipment, etc.

Table 2: Schedule of activities for packaging and mounting of FO sensors on board a metal Navy vessel.

No	ACTIVITY	TIME, (Days)	STAFF	COMMENTS
1.	Detailing plan for fibre location and orientation, identify obstructions, temporary removal of equipment, etc.	1–2 or more	(2) Navy + (2) SHM Team*	Initial area plan for SHM on a vessel would have been made before preparing fibre sensors.
2.	Draw a surface grid for the optical fibre location and remove the surface coating to leave the bare surface [19].	1–2	(2) Navy + (1) SHM Team	Theoretically, 1 day should be sufficient. The job could be physically very demanding.
3.	Surface treatment – grit blasting to Sa 2 ½ finish[15], area width approx. 25 mm (for each fibre length), clean and apply adhesion promoter, dry.	0.5	(1) Navy + (2) SHM Team	Requires attention - Good and uniform surface treatment should provide durable adhesion of fibres (>10 years).
4.	Apply to above prepared surface all fibres wound on the mandrels. This is to follow with complete lay-up sequence including the vacuum bag.	0.5	(3) SHM Team	Activities 3 & 4 should essentially be completed in 1 day. That removes the risk of surface contamination.
5.	Infuse with resin and cure overnight.	1	(3) SHM Team	If cold weather is anticipated protect the work area overnight from exposure.
6.	Removal of disposable materials, and application of 2 coats of primer. Navy to finish with top coat to match.	1	(3) SHM Team	-
7.	Test the sensor system operation, re-test after resin cure (i.e. 7 days later), save data as REFERENCE and use for comparison with future test for either structural or sensor degradation. Provide for long-term storage of connectors.	2	(1) Navy + (2) SHM Team	Having splice fragility sorted-out before-hand, all should operate satisfactorily. Some additional surface protection may be considered for fibres against accidental damage or exposure to heavy traffic.

*Initially, recommended a mix of scientists specialising in optical sensors and advanced composite materials.

15 **Sa** *2 ½*, Very thorough blast cleaning. Mill scale, rust and foreign matter shall be removed to the extent that the only traces remaining are slight stains in the form of spots or stripes. Finally, the surface is cleaned using either a vacuum cleaner, clean dry compressed air or a clean brush. It shall then correspond in appearance to the prints designated Sa *2 ½*.

5. Discussion

The work described in this report details a new approach for the packaging and mounting of a large number of sensors to either metal or composite structures. The principal drivers addressed were the technique's ease of use and simplicity of sensor application, low cost of materials, commercial availability and general familiarity of the technique within the composite industry. The long-term performance of the system especially durability, repeatability and reliability is beyond the scope of this project and remains to be addressed.

Presently, most issues dealing with the technical aspects of the packaging technique are thought to be resolved and the initial results point to its suitability for the purpose. However, a few areas are highlighted for attention. One of those relates to physical weakness of the fibre in the coating-stripped region. This weakness is probably the most current critical issue and future activities should focus on improving the sensor robustness during the installation and subsequent service operation. The current work efforts focussed on improving the handling of a fibre sensor by splicing it with 900 μm thick optical fibre patch cord and integrating a part of this cable and the splice into the resin infused layer. This improved mechanical durability / strength of the fibre sensor markedly.

Unfortunately, the first set of experiments using the mini-VARTM technique showed that even a gentle resin infusion which exerts no apparent tension on the fibre can, under vacuum pressure, cause a failure at the splice. This probably occurs due to localised bending at the splice caused by external pressure acting on the bag. Furthermore, mechanical tests confirmed that fibre breaking can also occur under tensile loading in the sensor grating region.

Common to both, the fusion splice and the Bragg grating regions, is the fibre weakness due to the buffer coating being stripped in preparation for splicing or writing the sensor grating. For more reliable and durable performance, it would be advisable to use draw-tower gratings in which the grating is written during fibre manufacture, before the fibre coating is applied. Also for applications of OF sensors to larger structures it should be possible to acquire, from the supplier, the required number of sensor arrays (splice-free) with set distances between the end of protective patch cord cable and the beginning of the first sensor gratings.

Nevertheless, in this case it is useful to have identified these weaknesses at this stage of the development because if left unnoticed such failures in service are costly and difficult to rectify.

In this work, due to the identified fibre weakness, there were a limited number of specimens available for mechanical evaluation. Therefore, a statistically valid sample population could not be tested and for that reason the results presented should be treated as indicative only. It would be useful to produce additional specimens prepared as suggested above and subject them to the same test protocol.

Other relevant points that need to be mentioned here but have not specifically been addressed in this work are: *birefringence*, *temperature compensation* and *strain transfer mechanism* (i.e. structure-to-sensor).

(i) Birefringence results when isotropic materials are deformed in a way such that the isotropy is lost. Typical examples in this case may include fibre stretching, bending, compression or combinations thereof. This undesirable effect causes a spectrum to change profile due to the induced strain gradient which could make identification of the Bragg-characteristic peak difficult. The literature has documented cases and discusses several solutions [5, 20-22]. In the limited study described in this report, this behaviour was not observed. If birefringence does occur then one simple solution that may help to provide a uniaxial strain response to loading along the axis of the optical fibre would be to cover the localised area containing the Bragg grating in a Teflon sleeve as shown in Figure 27. The Teflon sleeve would prevent resin bonding to the fibre grating area and thus prevent transverse forces acting on the fibre to cause Birefringence. The response of the fibre would then be governed solely by the axial extension of the fibre.

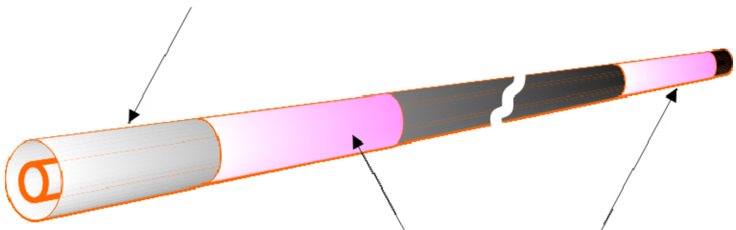

Figure 27: Proposed solution to potential birefringence issues in FBGs.

(ii) Some form of temperature compensation should also to be considered for FBG sensors applied to large-scale structures for long-term sensing. The literature reports that '… *an uncompensated FBG at 1550 nm band has an approximately 1 nm shift of Bragg wavelength over 100ºC temperature range …*[6]'.

In the case proposed in this study, the sensors are applied using a surface attachment method. Therefore, it could reasonably be expected that due to solar heating/cooling effects, fast changes and differential lag in temperature may occur at the surface which affect the sensor response. Since the literature does not propose a specific and universally accepted solution to this problem this issue alone could require a separate investigation. One solution is to incorporate some strain isolated FBG sensors in the array for temperature compensation.

(iii) Losses in strain transfer from the structure to the sensor should be avoided whenever possible. Those losses are most evident in applications which utilise various layers of bonding materials which are placed between the structure and the fibre sensors. In the method described in this report, the initial design has considered such potential problems and the issues are resolved by simply placing the fibres directly onto the structure before resin infusion.

6. Conclusions

A simple and easy-to-follow technique has been proposed for both packaging and bonding of FO sensor arrays on large-scale structures. The laboratory-based concept demonstration has shown the potential of a vacuum-assisted, epoxy resin infusion technique for *in-situ* bonding of long arrays of FBG sensors over large areas. All of the required materials are low cost, commercially available and the technique is familiar to users throughout the composite industry.

The loading study on the coupon tests, however, has identified a susceptibility of the fibres to breaking in the splice region. This issue should be investigated further and resolved before any commitments to large-scale SHM studies are considered. Otherwise, the initial results are encouraging. The FO sensor fitted to the sample exhibits a linear strain response, the resin shows no creep or hysteresis when loaded to about 5500 $\mu\varepsilon$ which is well above the anticipated maximum operational strain.

The main issues for transferring this technique from the laboratory to a structure in service have also been addressed in this work. A methodology for the safe transportation of the long fibre arrays without dislodging the fibres from their original placement has been demonstrated. The VARTM technique was simulated in the laboratory over a large area with minimal adjustments to account for the attachment length or work conditions. The method is suitable for retrofitting to existing structures in service that require long-term SHM over large areas or for inclusion between the surface and protective layer of a newly-constructed sub-structure.

To conclude, the method is simple to follow and avoids complexities especially with management of long fibre sensors in the field. Many of these sensors can be applied simultaneously, therefore the whole packaging and mounting procedure for applying an OF based SHM system can be completed in the shortest possible time. In case of naval ships, the work could hypothetically be completed during a scheduled call to port.

A further experimental program is recommended in the proceeding section to transition the work from a concept demonstrator to a large-scale SHM application.

7. Recommendations for Further Work

The following recommendations are suggested to resolve the current issues and improve the current performance and scope of the newly developed technique for large-scale resin packaging and mounting:

- Address the weakness in the splice region during the vacuum-assisted resin infusion process.
- Produce a new set of test specimens and repeat / extend the testing program by simulating service conditions. Apply commercially-available sensor packages alongside the DSTO developed procedure to allow comparison between different techniques / systems.

- Consider the effects of temperature on the FO sensor measurements by simulating service conditions. Develop an appropriate testing regime and suggest suitable methods for passive temperature compensation.
- Investigate the possible occurrence of birefringence and its effects on the measurements. Offer solution(s) if problems are likely to arise.
- Explore the long-term durability and reliability of the technique by initially setting up a laboratory test program followed by installation of the sensors on a large composite / metal structure for exposure to real service conditions. Also, applications to vertical and overhead surfaces should be investigated.

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Appendix A: A List of Suitable Resin Systems for Fibre Packaging and Mounting

	Manufacturer & Product no.	Chemical Type, Resin	Cure/Handle time	Viscosity, (cP)	Shear Strength, (MPa)***	Suitability
1.	3M[16], Scotch-Weld, CA7	Methyl-CA*, 1-part system	1–30 sec	15–40	6.2	Excellent adhesion to metals, plastics, rubbers
2.	3M, Scotch-Weld, CA8	Ethyl-, CA, 1-part system	5–40 sec	70–130	6.2	Slower setting, excellent adhesion to metals, plastics, rubbers
3.	3M, Scotch-Weld, CA40	Ethyl-CA, 1-part system	3–20 sec	20	5.5	Fast setting, excellent adhesion to many substrates, including flexible vinyl and EPDM rubbers
4.	Loctite[17] 290	Acrylic, Dimethacrylate ester, Anaerobic**, 1-part system	~ 30–60 min, Designed for small gaps <1 mm, but cures faster with temp and adding activator 7649	20–55	—	Designed for the locking and sealing of threaded fasteners due to low viscosity and capillary wicking action
5.	Loctite 609	Acrylic, Methacrylate ester, Anaerobic, 1-part system	~ 30–60 min, Designed for small gaps <1 mm, but cures faster with temp and adding activator	110–140	10.2	Designed for the bonding of metal cylindrical fitting parts.
6.	Loctite 4011	Ethyl-, CA, 1-part system	~ 10–40 sec, faster cure at higher humidity	90–140	5–15 (Phenolic)	Designed for the assembly of difficult to-bond materials which require uniform stress distribution and strong tension and/or shear strength.
7.	Loctite 4061	Ethyl-, CA, 1-part system	~ 10–60 sec, faster cure at higher humidity	10–30	5–15 (Phenolic)	Designed for bonding of plastics and elastomeric materials
8.	Loctite 4501	Ethyl-, CA, 1-part system	~ 1 min–6 hours, faster cure at higher humidity	10–25	8.5–11.9 (Phenolic)	A wicking viscosity formulated to cure for longer periods of time
9.	Permabond[18] A126	Acrylic, Single part**	~ 1–3 hours working strength, faster with surface activator A905 or heat	30	21 (Steel, Collar and Pin)	A high-strength anaerobic adhesive for permanent assembly of coaxial assemblies or threaded metal parts
10.	Permabond 101	Ethyl-, CA, 1-part system	~ 5–10 sec (Phenolics)	1–3	12–14 (Phenolics)	A low viscosity, wicking or penetrating applications, suitable for use on plastics, rubber and metals
11.	Permabond 105	Ethyl-, CA, 1-part system	~ 5–10 sec (Phenolics)	30–50	12–14 (Phenolics)	A low viscosity, wicking or penetrating applications, suitable for use on plastics, rubber and metals
12.	Permabond 790	Ethyl-, CA, 1-part system	~ 3 sec (Phenolics)	2	20 (Phenolics)	A low viscosity, bonds substrates such as plastics, metals, ceramics and elastomers
13.	FGI[19] – Epoxy, Various Systems	Epoxy, 2-part	Many options, ~ min to hours	Starts at ~ 130	High	High strength on many materials, surface preparation critical
14.	SIKA[20] – Sikadur-52 Epoxy Systems	Epoxy, 2-part	27 min @ 20°C 16 min @ 35°C	110 @ 35°C 300 @ 20°C	High	High strength on many materials, surface preparation critical

*Cyanoacrylate (Superglue), **Cures in the absence of oxygen, ***Overlap Shear Strength on ABS @ RT.

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[16] 3M Scotch-Weld, Structural Adhesives, Product Selection Guide,78-9236-7114-9, © 2008 3M, http://multimedia.mmm.com/mws/mediawebserver.dyn?6666660Zjcf6lVs6EVs66SONLCOrrrrQ-

[17] Loctite is a Trademark of Henkel Corporation, http://www.henkel.com/cps/rde/xchg/henkel_com/hs.xsl/index.htm

[18] Permabond Engineering Adhesives, http://www.permabond.com/default.htm

[19] Fiber Glass International, http://www.fgi.com.au/files/images/stories/pdfs/products/resins/Epoxies.pdf

[20] SIKA, Sikadur-52, http://www.sika.com.au/cmc/Datasheets/tds/Sikadur52_tds.pdf

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Sensor networks, optical fibres, structural health monitoring, Bragg gratings

19. ABSTRACT

A simple and inexpensive method has been developed for the application and bonding of optical fibre sensor networks to large structures for Structural Health Monitoring applications. The method makes use of a vacuum-assisted infusion technique using a low-cost epoxy resin which was found suitable for surface attachment. Mechanical tests showed no creep of the cured resin, and the response of Bragg grating based sensors was linear up to 5500 με. There was no hysteresis in the response and the sensitivity displayed at least equals that of a standard electrical resistance gauge.

A system for the management and transport of long optical fibres with arrays of sensors was proposed which facilitates safe and easy movement of all sensors from production to application. During application, the same resin infusion technique can be adapted to account for parameters in the size and shape of the structure and the operating environment. A laboratory simulation showed that sensors can be bonded over large distances (>10 m) thus making a large-scale, optical fibre sensor network feasible. This work has also revealed a tendency of the fibre to break under load in the splice region where it is connected to the cabled fibre. This is expected as it is the weakest region of the fibre and future work will focus on isolating this region of the packaging from the strain experienced by the structure to which it is bonded.

Finally, the report lists other recommendations for further work which includes an evaluation of the long-term performance of this technique.